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STUDIES ON CAPACITIES OF SOILS FOR IRRIGATION WATER, AND ON A NEW METHOD OF DETERMINING VOLUME WEIGHT

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INTRODUCTION

In connection with a study of the economical duty of water for alfalfa in Sacramento Valley, California, conducted from 1910 to 1915 as a part of the Cooperative Irrigation Investigations in California [1] certain observations were made, and methods devised which it seemed could be better presented and described in a separate paper than as a part of the general report of the study. It is realized that some of the data presented suggest ideas concerning soil properties which are not fully established by the preliminary investigations here reported. The observations are presented in two parts: (1) Studies on the capacities of soils for irrigation water, and (2) a new method of determining the volume weight of soils.

PART I.—STUDIES ON CAPACITIES OF SOILS TO RETAIN IRRIGATION WATER [2]

THEORETICAL DISCUSSION

That soil water is held in the form of minute films about the soil particles and in the interstitial spaces is a matter of common knowledge. The maximum capacity of soils to hold water in the capillary form may be limited by the total interstitial space in the soil rather than by the total external surface area of the soil particles (*4*).[3] It is therefore obvious that the volume weight of soil in place may be an important indicator of its water-holding power. The various laboratory methods which have been used to determine the maximum retentive power of soils for water usually give results which are far in excess of the retentive

[1] The Cooperative Irrigation Investigations in California are carried on by the Division of Irrigation Investigations, Office of Public Roads and Rural Engineering, United States Department of Agriculture, in conjunction with the California State Department of Engineering and the University of California Agricultural Experiment Station.

[2] For a full report of general studies referred to herein, see (*1*) in "Literature cited," p. 34.

[3] Reference is made by number (italic) to "Literature cited," p. 34-35.

powers of the same soils under field conditions because, first, they consider a very short column of soil which is acted upon by special capillary forces; and, second, the samples of soil used have in most cases volume weights which are much lower than those obtaining in the undisturbed condition. It is desirable, especially where irrigation is practiced, to have accurate knowledge of the maximum water-holding capacity of the soil in place. Burr (*5*) found the maximum capacity of a fine, sandy loam (loess) to be 16 to 18 per cent of the weight of the dry soil. Quantities of water found by various investigators after heavy irrigations or rainfall (*2, 7, 8, 9, 11, 12*) seem to be in agreement with the results of Burr's experiment. Indirectly, therefore, the maximum water capacities of soils in place have been determined by a number of workers under various conditions.

The optimum quantity of water to add to a given depth of soil in a single irrigation is dependent on the moisture content of the soil before irrigation and its maximum water capacity.

Let P = the percentage of water to be added;
W = the weight of soil to be moistened;
w = the weight of water to be applied.

Then $P \times W = w$ (1)

Since the quantity of water applied to a soil is usually expressed in depth over the surface, it is desirable to so express the quantity here needed.

Therefore let A = the area of land to be irrigated;
D = the depth of soil which needs water;
Vw = the volume weight of the soil;
d = the depth of water to be added;

Then $W = VwAD$ and $w = Ad \times 1$

Consequently, by substituting for W and w in equation one, their values as above, we have

$P \times VwAD = Ad$ and $d = P \times Vw \times D$ (2)

By taking D as 12 inches and assuming several values of Vw, figure 1 has been prepared from equation 2. For a given value of Vw the number of inches of water necessary to add a given percentage of moisture to 1 foot of soil may be readily determined.

EXPERIMENTAL CONDITIONS

The investigations here reported were made under the following conditions: First, on a number of alfalfa fields in Sacramento Valley representative of the best practice there; second, on 0.25-acre plots of the irrigation tract at the University of California farm at Davis; and third, on the 0.4-acre plots of a temporary experimental tract about 4 miles northeast of Willows, also in Sacramento Valley.

The soil of the typical farms ranges from silt loam underlain with fine sandy loam to heavy clays. The upper 2 feet of the Yolo loam in the

irrigation tract at the University farm is very uniform in texture; the third- to eighth-foot sections consist of fine sandy loam which is pocketed at irregular intervals with coarse sand and clay loam, below which is a heavy clay loam extending from 9 to 20 feet or more below the surface. The Tehema clay of the Willows tract is impervious to water and is very hard when dry.

Strictly speaking, the quantities of water accounted for, as given in the following pages, except as noted in the sixth and seventh columns of Table II, are a little low, since they do not include the water used by the plant immediately after irrigation. Upon the basis of experiments previously conducted at Davis (*6*), a total of approximately 1.08 inches of water was evaporated and used by the alfalfa during the first four

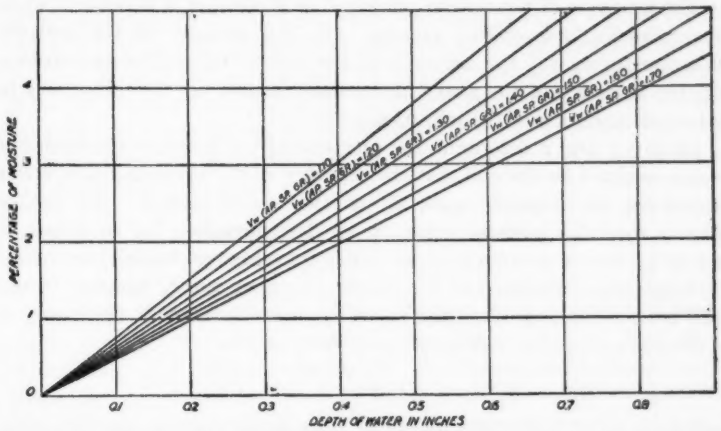

FIG. 1.—Diagram for determining the depth of irrigation water in inches necessary to add a given percentage of moisture to 1 foot of soil.

days after irrigation, the average time which elapsed between irrigation and the collecting of soil samples for moisture determinations. Including these probable evaporation losses, the total quantities and percentages of water accounted for are given in the sixth and seventh columns of Table II. When the average depth of irrigation water applied was small, as in the clay soils, the percentage loss of water during the first four days after irrigation was relatively high; consequently the percentages accounted for as given in the seventh column of Table II are relatively high for heavy soils, varying from 41.5 in the silt-loam soils to 69.4 in the clay soils. However, since practical considerations involved in irrigation farming demand that the water supply of the plant be furnished at different periods, the quantities of water stored in the soil by each irrigation, as indicated in column 5 of Table II (not including evaporation) and in Tables III and IV, may well be considered in each case representative of the effective irrigation. Moreover, since the studies

were all made in connection with the growth of but one crop (alfalfa), and as the time of observation after irrigation was made as nearly as possible the same, it is believed that the results are comparable. The acre-inch equivalents of the percentages before and after irrigation for each acre-foot of soil were calculated by using equation 2, deduced on page 3. The volume weights (*Vw*) used represent the density of the soil in place, except in a few cases as noted. In order to facilitate comparison with quantities of water applied in irrigation, and also with the total pore space of the soil, the quantities of moisture found before and after irrigation are presented in terms of acre-inches per acre-foot of soil.

PRECISION OF RESULTS

The precision of the results presented in this paper is dependent upon the following independent factors: (1) The accuracy of the moisture determinations, (2) the accuracy of the volume weight determinations, (3) the accuracy of the water measurements, and (4) the uniformity of lateral distribution of the irrigation water.

Factors 1 and 2 determine the precision of the absolute quantities of water retained by the soil, but the accuracy of the percentages of water accounted for depends upon all of the above factors. By use of Peter's formula [1] probable-error (*p. e.*) determinations for each foot of soil in 57 sets of six observations indicate average probable-error values for single observations (*r*) of ± 1.32 and ± 1.52 per cent of moisture before and after irrigation, respectively. The probable error of the mean of *n* determinations (*ro*) calculated from the relation:

$$ro = \frac{r}{\sqrt{n}}$$

indicates for the average number of borings per field or plot in which $n = 36$ average probable-error values of ± 0.22, and ± 0.25; for a type of soil *n* averages 114 and the probable-error values are $= \pm 0.12$ and ± 0.14, respectively, from which the probable error of the difference in moisture content before and after irrigation $= \pm 0.18$ per cent of moisture.

By using 1.40 as a mean volume weight, ± 0.18 per cent of moisture is equivalent to ± 0.03 acre-inch of water per acre-foot of soil. The average probable error of the volume-weight determinations (± 0.01) equivalent to $+0.002$ acre-inch of water per acre-foot of soil is too small to be significant. Hence, the average probable error of the increase in water due to irrigation $= \pm 0.03$ acre-inch for each acre-foot of soil. Upon this basis the chances are only 1 to 1 that increases of 0.03 inch for each foot of soil as given in the averages for the various types are due to the

[1] $r = 0.8453 \times \frac{\Sigma V}{\sqrt{n(n-1)}}$ where r = the probable error of a single observation;

$ro = 0.8453 \times \frac{\Sigma V}{n\sqrt{(n-1)}}$ ro = the probable error of the arithmetic mean of n observations;

ΣV = the sum of the residuals without regard to sign;

n = the number of observations.

application of water. Also the chances are 823 out of 1,000 that increases of 0.06 inch per foot are due to the irrigation, and 957 out of 1,000 that increases amounting to 0.09 inch were caused by irrigation.[1]

The probable error of the percentage of water accounted for can be only estimated since the water measurement data at hand do not make possible an accurate determination of the probable error of this factor. Moreover, it is dependent on uniform lateral surface distribution, which is, in fact, seldom attained. The field observations upon some of the tracts warrant the conclusion that lack of uniformity in lateral distribution [2] is responsible for the apparent discrepancies in the percentage of water accounted for.

A further test of precision was attempted by making three borings at one time, each within a distance of 6 feet of the other two, and calcuating the mean deviation of each determination from the average of the three. Thirteen sets of such determinations to a depth of 6 feet gave an average deviation of ± 0.62 per cent of moisture, an average probable error for a single observation of ± 0.66 per cent of moisture, which is approximately one-half of the probable error found in connection with six determinations scattered over an entire field representing an area of approximately 5 acres.

RESULTS ON TYPICAL ALFALFA FIELDS

EXPERIMENTAL CONDITIONS

The soils of these fields are divided into four general classes, notwithstanding some variation in physical properties of different types of soil within one class. While examining the data presented in Tables III and IV, reference should be made to Table I, which contains the volume weights and moisture equivalents (*3*) of the soils considered. It is to be noted that the volume weights vary from 1.10 to 1.75 and that the silt-loam soils are lighter than the clay loams and clays. These observations are not in accord with the ideas generally entertained concerning the relation of volume weight to soil texture.

[1] It must be remembered that, because of variations in soil, number of borings, and other less important factors, these values of the probable error do not apply equally to each type of soil given. Where the number of borings differs greatly from 114 (the average used) a more accurate value of the probable error may be obtained by multiplying 0.03 by the ratio of the square roots of the mean, 114, and the number of borings made in a given type of soil. For example, the averages for the Willows experimental tract given at the bottom of Table IV are based upon 284 borings. The probable error of the increase is therefore ± 0.019 inch per foot of soil. The minimum difference observed is 0.04 inch. The ratio of this difference to the average probable error of the difference is 2.1, which means that the chances are 843 out of 1,000 that the minimum difference was due to the irrigation.

[2] It is recognized that the degree of uniformity in lateral distribution which can be attained frequently determines the quantity of water applied per irrigation.

TABLE I.—*Volume weight of the upper 6 feet of different soils at depths varying from 1 to 9 feet, together with the moisture equivalent. Observations made upon soils from typical alfalfa farms in Sacramento Valley, Cal., 1913, 1914, and 1915*

Name and location of tract.	Volume weight of soil.	How moisture equivalent is expressed.	Moisture equivalent (3).									Averages.
Depth at which sample was taken.....feet..			0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	
SILT-LOAM SOILS HAVING FINE SANDY-LOAM SUBSOILS												
Wigno, Los Molinos.....	1.10	Per cent.....	24.18	24.45	23.62	24.20	21.37	16.42	.....	.....	.....	22.37
		Inches per foot of soil.....	3.18	3.22	3.12	3.17	2.80	2.16	.....	.....	.....	2.95
Griffes, Woodland.....	1.20	Per cent.....	20.64	21.22	20.78	19.89	16.57	18.58	23.58	23.13	24.40	20.98
		Inches per foot of soil.....	2.98	3.06	2.99	2.87	2.39	2.68	3.40	3.33	3.52	3.02
Average.....	1.15	.....do.....	3.08	3.14	3.06	3.02	2.60	2.42	3.40	3.33	3.52	2.98
SILT-LOAM SOILS												
Bundy, Los Molinos.....	1.30	Per cent.....	28.63	26.92	27.00	27.02	27.96	29.26	.....	.....	.....	27.80
		Inches per foot of soil.....	4.48	4.20	4.22	4.22	4.37	4.57	.....	.....	.....	4.34
Beck, Woodland.....	1.32	Per cent.....	25.68	25.18	28.03	26.59	21.45	.....	.....	.....	.....	25.39
		Inches per foot of soil.....	4.07	3.99	4.44	4.21	3.40	.....	.....	.....	.....	4.02
Hofhenke, Los Molinos.....	[a] 1.30	Per cent.....	.....	22.12	19.48	16.94	20.99	.....	20.73	24.73	22.67	21.09
		Inches per foot of soil.....	.....	3.45	3.04	2.65	3.27	.....	3.24	3.86	3.54	3.29
Average.....	1.31	.....do.....	4.28	3.88	3.90	3.69	3.68	4.57	3.24	3.86	3.54	3.88
SILT-LOAM SOILS NOT INCLUDED IN ABOVE GROUP												
Hughson, Woodland.....	1.21	Per cent.....	22.10	21.70	21.45	21.65	26.23	27.52	.....	28.00	24.80	24.18
		Inches per foot of soil.....	3.21	3.15	3.12	3.15	3.82	4.00	.....	4.07	3.61	3.52
Huartson, Gridley.....	[b] 1.32	Per cent.....	21.46	22.10	22.40	25.36	34.26	30.40	.....	.....	.....	26.00
		Inches per foot of soil.....	3.38	3.48	3.53	3.98	5.38	4.78	.....	.....	.....	4.09

CLAY-LOAM SOILS

O'Hair, Orland	[b] 1.33	Per cent	23.87	21.70	21.80	21.41	19.91	18.79				21.25
		Inches per foot of soil	3.18	2.89	2.90	2.85	2.65	2.50				2.83
Geer, Los Molinos	1.27	Per cent	24.75	26.71	25.90	26.54	27.76	27.64				26.55
		Inches per foot of soil	3.78	4.08	3.95	4.05	4.23	4.22				4.05
Guile, Woodland	1.40	Per cent	24.18	28.74	27.65	28.20	25.34	24.94				26.50
		Inches per foot of soil	4.07	4.83	4.65	4.73	4.26	4.20				4.43
Jackson-Woodard, Woodland	1.26	Per cent	30.31	31.65	31.79	29.92	28.70	29.14				30.25
		Inches per foot of soil	4.58	4.79	4.81	4.53	4.34	4.42				4.58
Wright, Dixon	[c] 1.50	Per cent	27.72	27.54	25.60	24.76	27.38					26.60
		Inches per foot of soil	4.98	4.96	4.61	4.46	4.93					4.79
Average	1.35	do	4.12	4.31	4.18	4.12	4.08	3.84				4.14

CLAY SOILS

Purdy, Willows	1.64	Per cent	21.02	28.62	34.20	25.65	32.44	32.52				29.08
		Inches per foot of soil	4.14	5.64	6.74	5.22	6.38	6.41				5.75
Tuttle, Willows	1.74	Per cent	19.30	20.38	20.79	23.68	24.85	27.48				22.75
		Inches per foot of soil	4.03	4.26	4.34	4.95	5.19	5.74				4.75
Average	1.69	do	4.08	4.95	5.54	5.08	5.78	6.08				5.25

CLAY SOILS SAMPLED AT DIFFERENT DEPTHS

Depth at which sample was taken inches			4	12	20	30	42	54				
Plots 3 and 4, Willows experimental tract	[d] 1.75	Per cent	19.70	20.38	22.64	21.98	22.09					21.36
	(1.778±0.006)	Inches per foot of soil	4.14	4.28	4.76	4.62	4.64					4.49
Plots 6 and 7, Willows experimental tract	[d] 1.75	Per cent	22.59	22.78	23.72	23.94	23.22					23.25
	(1.711±0.006)	Inches per foot of soil	4.74	4.78	4.97	5.03	4.88					4.88
Plots 11 and 12, Willows experimental tract	[d] 1.75	Per cent	20.70	21.10	22.74	23.76	25.60					22.78
	(1.743±0.017)	Inches per foot of soil	4.35	4.43	4.78	5.00	5.38					4.79
Average	1.75	do	4.41	4.50	4.84	4.88	4.97					4.72

[a] Based on 1913 field work as corrected by 1914 work on Bundy tract.
[b] Based on laboratory determinations with Bowman soil compactor.
[c] Work of 1913 corrected by 1913 and 1914 work on Jackson-Woodard tract.
[d] Average of determinations for entire field, 12 in number, used in calculations. Figures in parentheses are averages of three tests in the respective controls.

TABLE II.—*Number of irrigations per season and the average depths of water applied at each irrigation and retained by the upper 6 feet of soil for 15 typical alfalfa farms in Sacramento Valley, California, 1913, 1914, and retained by the upper 5 feet of soil on Willows experimental plot, 1915*

Class of soil and name of field.	Location.	Number of irrigations per season.	Average depths of water applied per irrigation.	Quantity of water retained by upper 6 feet of soil.	Quantity of water retained, including probable evaporation loss.	Percentage of average amount applied retained by 6 feet of soil.	Percentage retained, including probable evaporation loss.
			Inches.	*Inches.*	*Inches.*		
Silt-loam soils having fine sandy-loam sub-soils:							
Wigno	Los Molinos	4	18.25	4.89	5.97	26.8	32.7
Griffes	Woodland	2	11.78	5.14	7.22	52.1	61.4
Average			15.02	5.52	6.60	[a]36.8	43.9
Silt-loam soils:							
Bundy	Los Molinos	4	12.30	4.03	5.11	32.5	41.6
Beck	Woodland	2	9.52	4.19	5.27	44.0	55.3
Hofhenke	Los Molinos	4	16.62	4.51	5.59	27.1	33.6
Average			12.81	4.24	5.32	[a]33.1	41.5
Silt-loam soils not included in above group because of special conditions:							
Hughson	Woodland	2	39.50	8.20	9.28	20.7	23.5
Huartson	Gridley	[b]4	[b]7.20	4.19	5.27	58.1	73.2
Williams [c]	do	[b]4	[b]5.88	2.76	3.84	46.9	65.3
Clay-loam soils:							
O'Hair	Orland	3	4.16	2.65	3.73	63.7	89.7
Geer	Los Molinos	4	19.67	4.50	5.58	22.9	28.4
Guile	Woodland	2	6.61	4.70	5.78	71.1	87.3
Jackson-Woodard	do	3	8.04	3.33	4.41	41.4	54.8
Wright	Dixon	[d]8	5.44	2.31	3.39	42.4	62.3
Average			8.78	3.50	4.56	[a]39.8	52.0
Clay soils:							
Purdy	Willows	4	5.06	1.58	2.56	29.2	50.6
Tuttle	do	[e]4	4.38	2.93	4.01	66.9	91.4
Average			4.72	2.20	3.28	[a]46.8	69.4
Clay soils, Willows experimental tract:[f]							
Plots 3 and 4		12	2.00	0.54	1.62	27.0	81.0
Plots 6 and 7		8	3.00	1.07	2.15	35.7	71.7
Plots 11 and 12		4	6.00	1.57	2.65	26.2	44.1
Average			3.67	1.06	2.14	[a]28.9	58.3

[a] Averages determined by giving percentages weights proportionate to the amount of water applied.
[b] Sampled only for last three irrigations.
[c] Moisture determinations made to depth of only 3 feet.
[d] Sampled only for three irrigations.
[e] Sampled only for last two irrigations.
[f] Moisture determinations made to depth of only 5 feet.

In Table II are presented the number of irrigations which each tract was given annually, and the average depths of water applied per irrigation. These were found to decrease rapidly with the increase in fineness of the soil texture, averaging 15.02 inches for the silt-loam soils having fine sandy-loam subsoils and only 4.72 inches for the clay soil. The quantity of water retained by the upper 6 feet of soil also decreased with increase in fineness of texture.

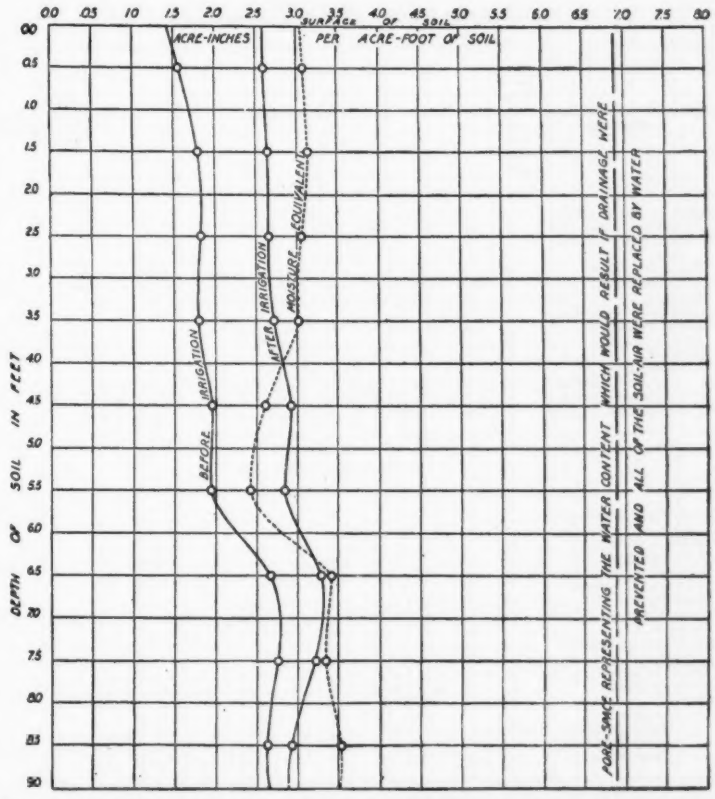
ACRE-INCHES PER ACRE-FOOT OF SOIL
SURFACE OF SOIL
DEPTH OF SOIL IN FEET
BEFORE IRRIGATION
AFTER IRRIGATION
MOISTURE EQUIVALENT
PORE-SPACE REPRESENTING THE WATER CONTENT WHICH WOULD REBUILT IF DRAINAGE WERE PREVENTED AND ALL OF THE SOIL-AIR WERE REPLACED BY WATER

FIG. 2.—Graphs of the water content before and after irrigation, moisture equivalent, and pore space of silt-loam soils having fine sandy-loam subsoils. Each water-content curve is the average of 62 borings.

SILT-LOAM SOILS HAVING FINE SANDY-LOAM SUBSOILS

In Table III and figure 2 are presented the results of 108 6-foot and 16 9-foot borings, thus making a total of 792 moisture determinations. It is of special interest to note that when these soils contained all of the water they would hold against gravity, an average of 2.73 inches for for each of the upper 6-foot sections, only 40 per cent of the pore space of the soil was filled. Apparently the maximum water capacity is

fixed by the total external surface area of the soil particles, the individual pore spaces being so large as to prevent the water films about the particles from consolidating sufficiently to fill appreciably the interstices.

TABLE III.—*Water content before and after irrigation, the moisture equivalent, and the pore space of the soils of typical alfalfa farms in Sacramento Valley, California, 1914. Averages for each foot of soil to a depth of 9 feet* [a]

[Results expressed in acre-inches per acre-foot of soil]

SILT-LOAM SOILS HAVING FINE SANDY-LOAM SUBSOILS [b]

Tract, location, and time of sampling.	Number of borings for soil samples.	Water content.									Moisture equivalent.	Pore space.
Depth of soil at which samples were taken, feet	.....	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5		
Wigneau tract, Los Molinos:												
Before irrigation	26	1.77	2.00	1.97	2.02	2.28	2.04	[c]2.67	2.76	2.62	[d]2.95	7.10
After irrigation	26	2.62	2.73	2.77	2.85	3.08	2.93	[c]3.28	3.21	2.91		
Increase	.....	.85	.73	.80	.83	.80	.89	.61	.45	.29		
Griffes tract, Woodland:												
Before irrigation	36	1.34	1.60	1.69	1.59	1.64	1.84	.....	.....	.....	[d]2.83	6.66
After irrigation	36	2.58	2.57	2.56	2.60	2.77	2.76	.....	.....	.....		
Increase	.....	1.24	.97	.87	1.01	1.13	.92	.....	.....	.....		
Averages:												
Before irrigation	62	1.56	1.80	1.83	1.80	1.96	1.94	2.67	2.76	2.62	2.89	6.88
After irrigation	66	2.60	2.65	2.66	2.72	2.92	2.84	3.28	3.21	2.91		
Increase	.....	1.04	.85	.83	.92	.96	.90	.61	.45	.29		

SILT-LOAM SOILS [e]

Bundy tract, Los Molinos:												
Before irrigation	24	2.54	2.86	2.84	2.84	2.97	3.12	3.19	3.50	3.50	[d]4.34	6.31
After irrigation	24	3.50	3.62	3.61	3.52	3.42	3.53	3.57	3.82	3.90		
Increase	.....	.96	.76	.77	.68	.45	.41	.38	.32	.40		
Beck tract, Woodland:												
Before irrigation	18	1.72	2.09	2.12	2.19	2.48	2.83	.....	.....	.....	4.02	6.18
After irrigation	18	2.97	2.84	2.83	2.85	3.01	3.12	.....	.....	.....		
Increase	.....	1.25	.75	.71	.66	.53	.29	.....	.....	.....		
Hofhenke tract, Los Molinos:												
Before irrigation	45	2.12	2.43	2.37	2.37	2.44	2.49	2.72	2.99	3.04	[f]3.29	6.32
After irrigation	45	3.27	3.29	3.04	3.00	3.04	3.09	3.26	3.30	3.35		
Increase	.....	1.15	.86	.67	.63	.60	.60	.54	.31	.31		
Averages:												
Before irrigation	87	2.13	2.46	2.44	2.47	2.63	2.81	2.96	3.24	3.27	3.88	6.27
After irrigation	87	3.25	3.25	3.16	3.12	3.16	3.25	3.42	3.56	3.62		
Increase	.....	1.12	.79	.72	.65	.53	.44	.46	.32	.35		

[a] See Table II for the number of times each of the above fields was irrigated, the average quantities of water applied, and the total amounts of water retained by the soil.
[b] These data are presented graphically in figure 2.
[c] From 7 to 9 feet average of only 8 borings.
[d] Upper 6 feet.
[e] These data are presented graphically in figure 3.
[f] Upper 9 feet, less first and sixth.

SILT-LOAM SOILS

In Table III and figure 3 are presented results of moisture determinations upon three tracts classed as silt-loam soils which are based upon 138 6-foot and 36 9-foot borings, making a total of 1,152 moisture determinations. The results for the upper 6 feet of soil as presented in figure 3

are based upon 174 borings and 1,044 moisture determinations, while those of the depth from 7 to 9 feet are based upon 36 borings and 108 single observations.

The curves of the silt-loam soils converge from the surface of the soil downward. This seems to be due in large measure to the fact that these soils do not dry out as rapidly at great depths as do the more porous fine

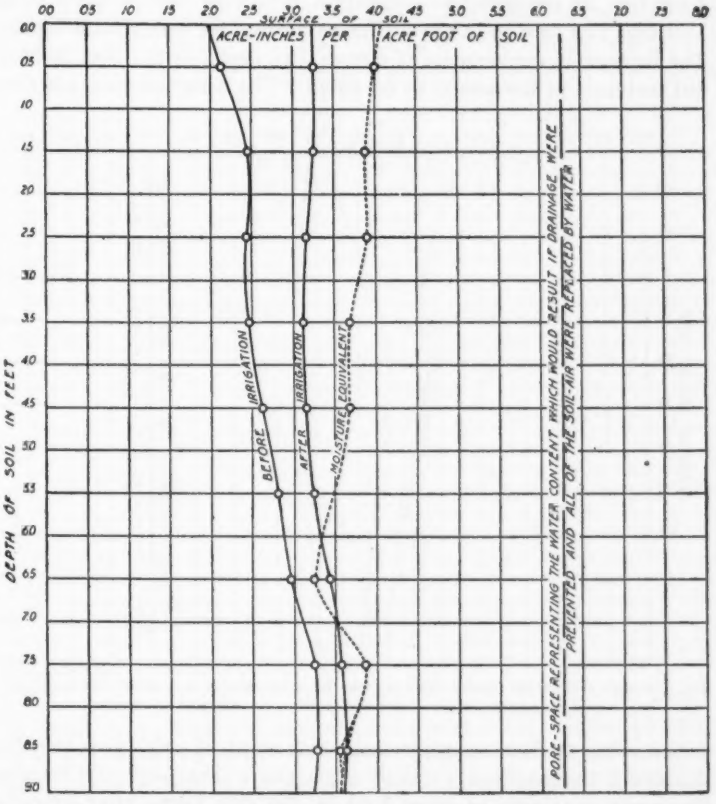
00 05 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
ACRE-INCHES PER ACRE FOOT OF SOIL
SURFACE OF SOIL
DEPTH OF SOIL IN FEET
BEFORE IRRIGATION
AFTER IRRIGATION
MOISTURE EQUIVALENT
PORE-SPACE REPRESENTING THE WATER CONTENT WHICH WOULD RESULT IF DRAINAGE WERE PREVENTED AND ALL OF THE SOIL-AIR WERE REPLACED BY WATER

FIG. 3.—Graphs of the water content before and after irrigation, moisture equivalent, and pore space of silt-loam soils. Each water-content curve is the average of 87 borings.

sandy-loam subsoils, since the observations after irrigation show very little decrease of water content with depth. As the soils are very uniform, it seems reasonable to conclude that their maximum capillary capacities were satisfied. The average amount of water held after irrigation was 3.20 inches per foot, or enough to fill 51 per cent of the pore space, as compared to 2.73 inches per foot, or enough to fill 40 per cent of the pore space for the loam soils having fine sandy loam subsoils.

CLAY-LOAM SOILS

In Table IV and figure 4 are given the quantities of water held before and after irrigation for five typical farms having clay loam soils as determined by 296 six-foot borings, making 1,776 single observations.

Figure 4 represents average results of the five clay-loam fields. The increase in water content varies from 1.35 in the surface to 0.28 in the sixth foot, as compared to a variation of 1.13 to 0.44 in the silt-loam soils and 1.04 to 0.90 in the silt loams having fine sandy-loam subsoils. The increase in convergence of curves with depth as the texture of the soil increases in fineness is to be noted. The water content after irri-

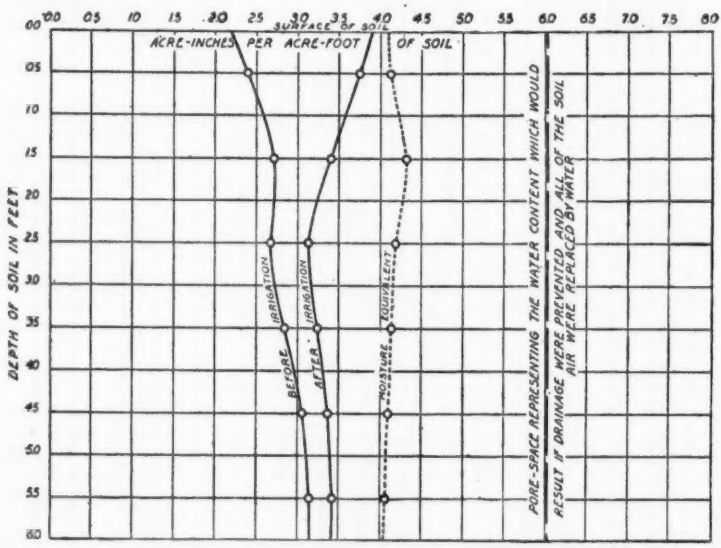
ACRE-INCHES PER ACRE-FOOT OF SOIL
SURFACE OF SOIL
DEPTH OF SOIL IN FEET
BEFORE IRRIGATION
AFTER IRRIGATION
MOISTURE EQUIVALENT
PORE-SPACE REPRESENTING THE WATER CONTENT WHICH WOULD RESULT IF DRAINAGE WERE PREVENTED AND ALL OF THE SOIL AIR WERE REPLACED BY WATER

FIG. 4.—Graphs of the water content before and after irrigation, moisture equivalent, and pore space of clay-loam soils. Each water-content curve is the average of 148 borings.

gation seems to decrease appreciably with depth of soil. It is therefore doubtful if the maximum capillary capacities of these soils were satisfied. The average amount of water held by the clay loams after irrigation was 3.49 inches per foot, or enough to fill 58 per cent of the pore space as compared to 40 and 51 per cent, respectively, in the first and second types of soil considered.

CLAY SOILS

It was pointed out above that the maximum water-holding powers of clay soils are sometimes limited by their pore space. This condition seems to apply to the soils described below, the volume weights of which were found to be unusually high. The total external surface area of

these soils is in all probability very high, to judge from their mechanical analysis, which showed 24.54 per cent of total sands, 40 per cent of silt, and 34.84 per cent of clay. Yet the quantities of water found in them both before and after irrigation were extremely low. This condition is especially evident when the results are recorded in percentages rather than in inches per foot, since the high volume weights increase their water content relatively when reported upon the latter basis.

The observations made upon clay soils are presented in Table IV and figures 5 and 6. Figure 5 is based upon 86 six-foot borings, making 516 moisture determinations, and figure 6 contains averages of 568 borings

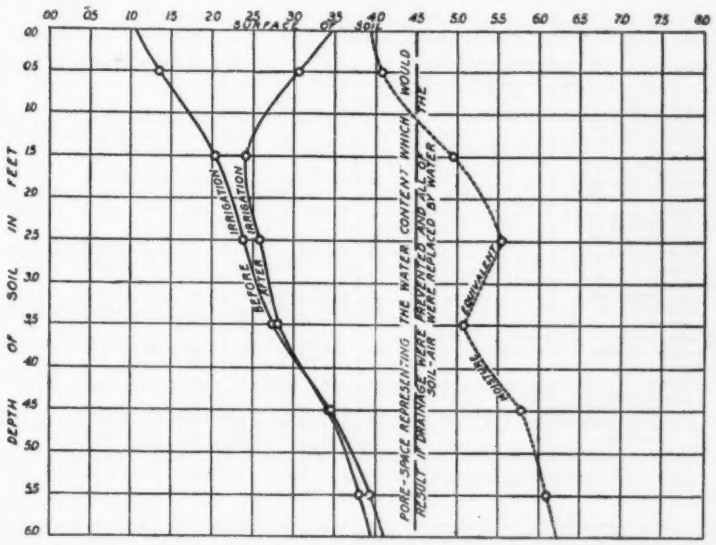
SURFACE OF SOIL
DEPTH OF SOIL IN FEET
BEFORE IRRIGATION
AFTER IRRIGATION
MOISTURE EQUIVALENT
PORE-SPACE REPRESENTING THE WATER CONTENT WHICH WOULD RESULT IF DRAINAGE WERE PREVENTED AND ALL OR SOIL-AIR WERE REPLACED BY WATER

FIG. 5.—Graphs of the water content before and after irrigation, moisture equivalent, and pore space of clay soils. Each water-content curve is the average of 43 borings.

in which 3,408 moisture determinations were made. Table IV reveals at a glance the striking fact that only the surface foot of soil was appreciably moistened by the irrigation water. It is doubtful if the capillary power of the surface foot was entirely satisfied; yet it held after irrigation 3.06 inches of water, or enough to fill 64.3 per cent of its pore space. The sixth foot, which was kept moist by the ground-water table, contained no gravitational water, but 86 per cent of its pore space was occupied by capillary water, leaving only 16 per cent of the 4.71 inches of pore space per foot of soil for air, or only two-thirds of one inch in twelve.

TABLE IV.—*Water content before and after irrigation, the moisture equivalent and the pore space of the soils of typical alfalfa farms in Sacramento Valley, California, 1913–1915. Averages for each foot of soil to a depth of 6 feet* [a]

[Results expressed in acre-inches per acre-foot of soil]

CLAY-LOAM SOILS, 1913–14 [b]

Tract, location, and time of sampling.	Number of borings for soil samples.	Water content.						Moisture equivalent in acre-inches per acre-foot of soil.	Pore-space acre-inches per acre-foot of soil.
Depth of soil at which samples were taken		0.5	1.5	2.5	3.5	4.5	5.5		
O'Hair, Orland:									
Before irrigation	27	1.46	1.83	2.07	2.69	3.21	3.51	3.39	6.10
After irrigation	27	3.14	2.51	2.40	2.71	3.21	3.44		
Increase		1.68	.68	.33	.03	.00	−.07		
Geer, Los Molinos:									
Before irrigation	48	2.60	3.06	2.40	2.44	2.66	2.67	4.05	6.36
After irrigation	48	3.67	3.86	3.07	3.17	3.27	3.21		
Increase		1.07	.80	.67	.73	.61	.54		
Guile, Woodland:									
Before irrigation	12	2.23	2.46	2.60	2.67	2.74	2.72	4.44	5.78
After irrigation	12	4.00	3.34	3.18	3.22	3.20	3.18		
Increase		1.77	.88	.58	.55	.46	.46		
Jackson-Woodard, Woodland:									
Before irrigation	36	2.46	2.79	2.92	3.02	3.12	3.25	4.57	6.42
After irrigation	36	4.04	3.52	3.28	3.28	3.31	3.46		
Increase		1.58	.73	.36	.26	.19	.21		
Wright, Dixon:									
Before irrigation	25	3.21	3.40	3.31	3.29	3.41	3.47	4.79	5.38
After irrigation	25	3.83	3.76	3.69	3.70	3.72	3.70		
Increase		.62	.36	.38	.41	.31	.23		
Averages:									
Before irrigation	148	2.39	2.71	2.66	2.82	3.03	3.12	4.25	6.01
After irrigation	148	3.74	3.40	3.12	3.22	3.34	3.40		
Increase		1.35	.69	.46	.40	.31	.28		

CLAY SOILS, 1914 [c]

Purdy, Willows:									
Before irrigation	24	1.30	1.99	2.39	2.82	3.71	4.36	5.73	4.71
After irrigation	24	3.03	2.12	2.51	2.79	3.54	4.06		
Increase		1.73	.13	.12	−.03	−.17	−.30		
Tuttle, Willows:									
Before irrigation	19	1.40	2.09	2.36	2.64	3.16	3.48	4.75	4.25
After irrigation	19	3.09	2.70	2.65	2.81	3.29	3.52		
Increase		1.69	.61	.29	.17	.13	.04		
Averages:									
Before irrigation	43	1.35	2.04	2.38	2.73	3.44	3.92	5.24	4.48
After irrigation	43	3.06	2.41	2.58	2.80	3.42	3.79		
Increase		1.71	.37	.20	.07	−.02	−.13		

[a] See Table II for the number of times each of the above fields were irrigated, the average quantities of water applied, and the total amounts of water retained by the soil.

[b] These data are presented graphically in figure 4.

[c] The plan of sampling the upper 2 feet of the clay soils was in 1915 changed from one sample in the middle of each foot-section to one in the middle of each 8-inch section, thus giving three samples in the upper 2 feet. The sixth foot was not sampled in 1915. These data are presented graphically in figures 5 and 6.

TABLE IV.—*Water content before and after irrigation, the moisture equivalent and the pore space of the soils of typical alfalfa farms in Sacramento Valley, California, 1913–1915. Averages for each foot of soil to a depth of 6 feet*—Continued

CLAY SOILS, 1915[a]

Tract, location, and time of sampling.	Number of borings for soil samples.	Water content.						Moisture equivalent in acre-inches per acre-foot of soil.	Pore-space acre-inches per acre-foot of soil. memm
Depth at which samples were taken, inches.....		4	12	20	30	42	54		
Plots 3 and 4, Willows experimental tract:									
Before irrigation.....	140	1.71	2.10	2.41	2.61	2.87	3.96	4.49	4.18
After irrigation.....	140	2.40	2.18	2.42	2.63	2.84	3.99		
Increase.....	.....	.69	.08	.01	.02	−.03	.03		
Plots 6 and 7, Willows experimental tract:									
Before irrigation.....	96	1.78	2.31	2.67	2.99	3.36	4.95	4.88	4.49
After irrigation.....	96	2.97	2.62	2.79	3.06	3.38	4.85		
Increase.....	.....	1.19	.31	.12	.07	.02	−.10		
Plots 11 and 12, Willows experimental tract:									
Before irrigation.....	48	1.45	1.97	2.38	2.62	2.93	4.08	4.78	4.35
After irrigation.....	48	2.91	2.52	2.50	2.73	3.06	3.99		
Increase.....	.....	1.46	.55	.12	.11	.13	−.09		
Averages:									
Before irrigation.....	284	1.63	2.13	2.49	2.74	3.05	4.33	4.72	4.34
After irrigation.....	284	2.76	2.44	2.57	2.81	3.09	4.28		
Increase.....	.....	1.11	.31	.08	.07	.04	−.05		

[a] The plan of sampling the upper 2 feet of the clay soils was in 1915 changed from one sample in the middle of each foot-section to one in the middle of each 8-inch section, thus giving three samples in the upper 2 feet. The sixth foot was not sampled in 1915. These data are presented graphically in figures 5 and 6.

The unusual conditions which were encountered in the Willows area during 1914 seemed to warrant further work upon this type of soil, and in 1915 twelve 2-inch, eight 4-inch, and four 6-inch irrigations were given to plots 3 and 4, 6 and 7, and 11 and 12, respectively, of the Willows experimental tract.

Three samples were taken in the upper 2 feet of soil—that is, one representing each 8-inch section.[1] The relatively small individual increases observed in plots 3 and 4, as compared to those in plots 6 and 7, are probably due in part to differences in soil compactness,[2] but the smaller unit application of water was in all probability the chief controlling factor. The total seasonal increase in the different plots—that is, the unit increase multiplied by the number of irrigations as shown in Table V—is relatively higher in plots 3 and 4.

[1] In examining the water contents presented in Table IV, it must be remembered that the results presented in the three columns at the reader's left are at the rate of the various numbers of acre-inches per acre-foot of soil, and must therefore be multiplied by 8/12 to get the actual increase in each of the individual 8-inch sections. This has been taken into account in the calculations of quantities of water accounted for, as presented at the bottom of Table II.

[2] The soil of plots 6 and 7 is less compact than that of the other plots. (See Table I.)

TABLE V.—*Total seasonal increases in irrigation-water content of the Willows experimental tract*

Plot No.	Number of irrigations.	Unit increase in water content.	Total seasonal increase.
		Inches.	*Inches.*
3 and 4	12	0.54	6.48
6 and 7	8	1.07	8.56
11 and 12	4	1.57	6.28

The averages presented at the bottom of Table IV and in figure 6 show, like those of the Purdy and Tuttle tracts, that but very little water passed below the surface foot of soil.

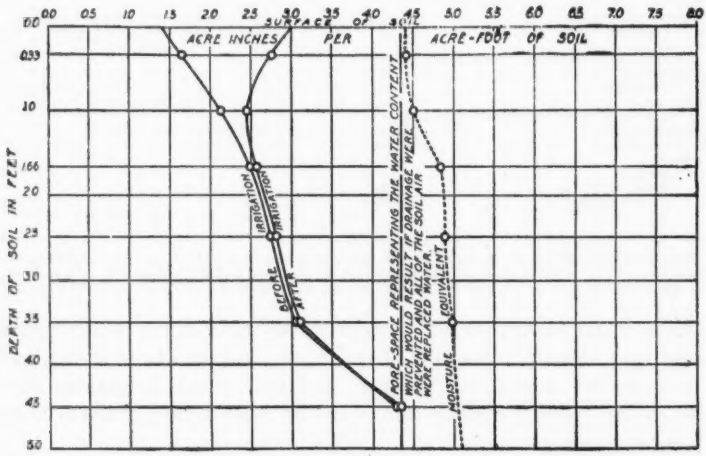
ACRE INCHES PER ACRE-FOOT OF SOIL
DEPTH OF SOIL IN FEET
IRRIGATION
BEFORE IRRIGATION
AFTER
PORE-SPACE REPRESENTING THE WATER CONTENT WHICH WOULD RESULT IF DRAINAGE WERE NOT PREVENTED BY THE SOIL AIR
MOISTURE EQUIVALENT

FIG. 6.—Graphs of the water content before and after irrigation, moisture equivalent, and pore space of clay soils. Each water-content curve is the average of 284 borings.

RESULTS ON UNIVERSITY FARM, DAVIS

Among other reasons, the systematic plan of irrigation followed and the length of time covered in the Davis work make it desirable to present separately the results there obtained. No appreciable differences in volume weight were found, notwithstanding textural differences, the average volume weight of several observations being 1.28. Upon this value the calculations given in the following tables are based. The moisture-equivalent determinations as presented in Table VI were made of samples from each of the upper 12 feet of soil taken from single borings in three plots,[1] D, F, and H. Plots B, C, D, E, F, and G[2] are sufficiently alike in texture to be placed in one group, although some varia-

[1] See Table VII for explanatory note on the numbering of the plots.

[2] As plot A was given no irrigation water, it is not reported in this paper.

tion exists, especially in the depths from 4 to 9 feet. Averages of the moisture equivalents of plots D and F are used for this group, including plots B to G, but the individual determinations are given in Table VI to show the variation of texture which exists and for which due allowance must be made.

TABLE VI.—*Moisture equivalents for soils at the University Farm, Davis, Cal., at depths varying from 1 to 12 feet*

[Results expressed in terms of percentage by weight and of acre-inches per acre-foot of soil]

Depth of soil in feet.	Plot D (per cent).	Plot F (per cent).	Average of plots D and F.[a]		Plot H.	
			Per cent.	Acre-inches per acre-foot of soil.	Per cent.	Acre-inches per acre-foot of soil.
0. 5	23. 32	24. 44	23. 88	3. 67	28. 41	4. 37
1. 5	22. 00	21. 80	21. 90	3. 37	31. 70	4. 87
2. 5	21. 24	15. 96	18. 60	2. 86	34. 02	5. 23
3. 5	18. 93	11. 69	15. 31	2. 36	30. 47	4. 69
4. 5	16. 60	21. 52	19. 06	2. 93	31. 38	4. 82
5. 5	14. 08	16. 90	15. 51	2. 39	27. 23	4. 19
6. 5	14. 03	23. 84	18. 94	2. 91	29. 36	4. 51
7. 5	15. 28	26. 90	21. 09	3. 24	26. 92	4. 13
8. 5	12. 07	23. 12	17. 60	2. 71	26. 90	3. 98
9. 5	20. 44	21. 36	20. 90	3. 22	23. 22	3. 57
10. 5	26. 32	24. 50	25. 41	3. 91	20. 80	3. 20
11. 5	26. 36	24. 36	25. 36	3. 90	24. 77	3. 81

[a] The average value of the moisture equivalent as determined upon samples of soil from plots D and F are used to represent the moisture equivalent in plots B, C, D, E, F, and G.

The soil of plot H, classed by the Bureau of Soils of the United States Department of Agriculture as a Yolo loam, is distinctly finer in texture than that of the other plots, excepting a part of plot B. The differences in texture between it and the other plots are most readily appreciated by examination of the moisture equivalents of the two soils.[1] Averages of the results of three years' observations, representing the number of inches and also the percentages of the quantities of water applied which were retained by the upper 6 feet and the upper 12 feet of soil, are given in Table VII.[2] Assuming, upon the basis of the evaporation and transpiration experiments cited (*6*), that 0.7 inch of water was lost by evaporation and transpiration in the two days which elapsed between the time of irrigation and of sampling, plots B, C, and D retained in the upper 6 feet of soil an average of about nine-tenths of the water applied. Plots E, F, and G retained in the upper 6 feet nearly seven-tenths of the water applied, and the entire amount was apparently retained by the upper 12 feet. Likewise, plot H retained two-thirds of the water applied in the upper 6 feet of soil and nine-tenths in the upper 12 feet.

[1] Plot B, which lies nearest plot H, forms the division line between the two types of soil above mentioned.
[2] See (*1*, *p.* 10) for a discussion of Table VII.

TABLE VII.—*Number of acre-inches and percentage of the amount of water applied in each irrigation which was retained by the upper 6 feet and the upper 12 feet of soil, University of California farm, Davis, Cal. Averages for 1913, 1914, 1915*

Plot No.	Number of irrigations per season.	Depth of water applied at each irrigation.	Amount retained in upper 6 feet of soil.		Amount retained in upper 12 feet of soil.	
			Inches.	Percentage of quantity applied.	Inches.	Percentage of quantity applied.
		Inches.				
B (18, 29) [a]	2	6.0	3.81	63.5	(b)	.....
C (19, 28)	3	6.0	5.52	92.0	.....	.....
D (20, 27)	4	6.0	4.43	73.8	.....	.....
Average of 6-foot tests, plots B, C, and D	3	6.0	4.59	76.4	.....	.....
E (21, 26)	4	7.5	5.10	68.0	8.00	106.6
F (22, 25)	4	9.0	5.49	61.0	9.56	106.1
G (23, 24)	4	12.0	6.68	55.6	10.32	86.0
Average of 12-foot tests, plots E, F, and G	4	9.5	5.76	[b] 60.6	9.29	[c] 97.7
H (31)	4	15.0	9.24	61.6	13.09	87.2

[a] For convenience in referring to the plots, letters are used instead of the numbers in parentheses. The latter were used on page 10, California Department of Engineering Bulletin 3.

[b] Borings were made only to a depth of 6 feet in plots B, C, and D.

[c] Group averages obtained by giving plots percentages and weights proportional to quantities of water applied.

The amounts of water held by each foot of soil before and after irrigation and the average increases which were found for the various treatments are set forth in Table VIII. For ease of comparison these data are presented graphically in figures 7 to 12. The water contents of plots B and D are compared in figure 7. The soil of plot B being finer in texture than that of plot D, especially below 3 feet, accounts for the higher water content both before and after irrigation. Variation in the soil of plot B is probably the cause of an apparent discrepancy in the relative amounts of water accounted for. The comparison of plots C and D presented in figure 8 indicates that plot C became drier before irrigation than did plot D, which accounts for the greater amount of water being retained by plot C since each plot contained about the same quantity after irrigation. Figure 9 indicates that the upper 6 feet of plots E and G were moistened to their full capillary capacity. It is likely that the clay-loam stratum of the seventh foot in plot G by retarding downward movement caused some gravitational water to be held in the fifth and sixth foot section till the time of sampling. The effect of the large irrigations of plot G is evident in the great difference between the moisture contained, before and after irrigation, in the third to the sixth foot sections. Figure 10 shows that the 12-inch irrigations of plot G caused slightly greater increases than the 9-inch applications of plot F in the second to seventh foot, below which the increases were very irregular.

TABLE VIII.—*Water content before and after irrigation of soils, University of California Farm, Davis, Cal. Average in each foot of soil to a depth of 12 feet for the years 1913, 1914, and 1915a*

[Results expressed in acre-inches per acre-foot of soil]

Plot number and irrigation treatment.	Time of sampling.	Number of borings.	Water content.												Total water at depths of—			See fig.
			0-6 ft.	7-12 ft.	0-12 ft.													
Depth at which samples were taken	feet.		0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5				
B, 2-6-inch irrigation	Before irrigation	14	1.78	2.03	2.14	2.46	2.37	2.13	.....	.....	.....	.....	.....	.....	12.91	.....	.....	7
	After irrigation	14	3.26	2.99	2.86	2.69	2.73	2.19	.....	.....	.....	.....	.....	.....	16.72	.....	.....	
	Increase	.....	1.48	.96	.72	.23	.36	.06	.....	.....	.....	.....	.....	.....	3.81	.....	.....	
C, 3-6-inch irrigation	Before irrigation	21	1.68	1.93	1.91	1.80	1.43	1.29	.....	.....	.....	.....	.....	.....	10.04	.....	.....	8
	After irrigation	21	3.34	2.99	2.82	2.45	2.10	1.86	.....	.....	.....	.....	.....	.....	15.56	.....	.....	
	Increase	.....	1.66	1.06	.91	.65	.67	.57	.....	.....	.....	.....	.....	.....	5.52	.....	.....	
D, 4-6-inch irrigation	Before irrigation	28	1.76	2.06	2.06	1.87	1.59	1.49	.....	.....	.....	.....	.....	.....	10.83	.....	.....	7
	After irrigation	28	3.30	3.06	2.75	2.26	2.02	1.87	.....	.....	.....	.....	.....	.....	15.26	.....	.....	8
	Increase	.....	1.54	1.00	.69	.39	.43	.38	.....	.....	.....	.....	.....	.....	4.43	.....	.....	
E, 4-7.5-inch irrigation	Before irrigation	28	1.95	2.16	2.08	1.85	1.73	1.63	1.47	2.81	3.24	3.63	4.25	5.10	11.40	20.53	31.93	9
	After irrigation	28	3.20	3.16	2.95	2.60	2.40	2.19	2.21	3.64	4.18	4.22	4.52	4.66	16.50	23.43	39.93	
	Increase	.....	1.25	1.00	.87	.75	.67	.56	.74	.83	.94	.59	.27	.44	5.10	2.90	8.00	.....
F, 4-9-inch irrigation	Before irrigation	28	1.85	2.04	1.92	1.76	1.87	1.59	2.56	3.38	2.84	4.04	4.53	4.69	11.03	22.04	33.07	10
	After irrigation	28	3.17	3.10	2.82	2.52	2.57	2.34	3.33	4.08	3.98	4.49	5.08	5.15	16.52	26.11	42.63	
	Increase	.....	1.32	1.06	.90	.76	.70	.75	.77	.70	1.14	.45	.55	.46	5.49	4.07	2.56	.....
G, 4-12-inch irrigation	Before irrigation	28	1.91	2.18	2.05	1.96	2.11	2.32	3.37	3.16	2.94	3.88	3.86	4.46	12.53	21.67	34.20	9
	After irrigation	28	3.24	3.30	3.04	2.99	3.23	3.41	4.22	3.77	3.76	4.32	4.32	4.92	19.21	25.31	44.52	10
	Increase	.....	1.33	1.12	.99	1.03	1.12	1.09	.85	.61	.82	.44	.46	.46	6.68	3.64	10.32	.....
Average	Before irrigation	147	1.82	2.07	2.02	1.95	1.85	1.74	2.47	3.12	3.01	3.85	4.21	4.75	11.46	21.40	32.86	11
	After irrigation	147	3.25	3.10	2.87	2.58	2.51	2.31	3.26	3.83	3.97	4.34	4.64	4.91	16.63	24.95	41.58	
	Increase	.....	1.43	1.03	.85	.63	.66	.57	.79	.71	.97	.49	.43	.16	5.17	3.55	8.72	.....
H, 4-15-inch irrigation	Before irrigation	28	2.30	2.76	3.77	3.67	3.82	3.92	4.16	4.03	3.86	3.92	3.92	3.78	20.24	23.67	43.91	12
	After irrigation	28	3.89	5.01	5.24	5.30	4.98	5.06	4.90	4.71	4.72	4.42	4.41	4.36	29.48	27.52	57.00	
	Increase	.....	1.59	2.25	1.47	1.63	1.16	1.14	.74	.68	.86	.50	.49	.58	9.24	3.85	13.09	.....

[a] In 1913 samples were taken only to a depth of 6 feet, and in 1915, 9 feet was the maximum depth of boring. Therefore results given for depths of 7 to 9 feet, inclusive, are based upon two years' work, and from 10 to 12 feet upon only one year's work.

The upper 6 feet of the water-content curves in figure 11 plotted from the averages in Table VIII are based on 294 borings and 1,764 moisture determinations; the section from 7 to 9 feet is based upon 120 borings and 360 single observations; and the depth from 9 to 12 feet represents averages of 48 borings and 144 moisture determinations. The curves for the upper 6 feet of plot H presented in figure 12 are based on 56 borings and 336 single observations; the section from 7 to 9 feet on 40 borings and 120 single determinations; and for the depth from 10 to 12 feet on 16 borings and 48 single moisture tests.

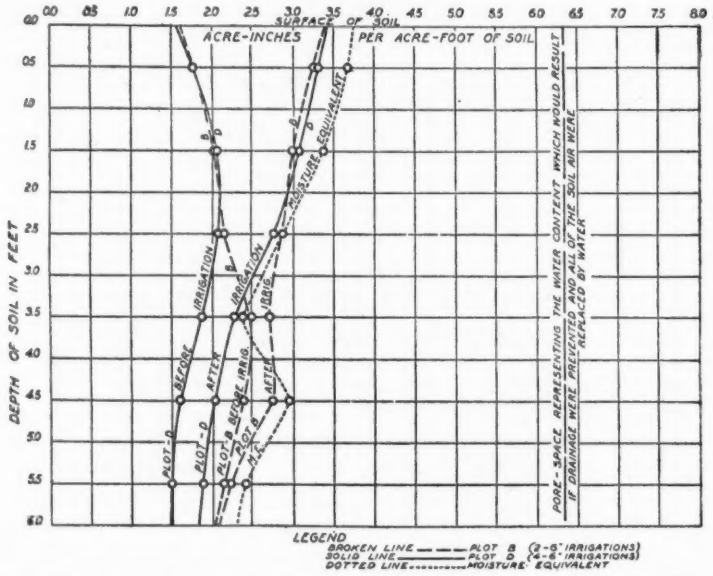
SURFACE OF SOIL
ACRE-INCHES PER ACRE-FOOT OF SOIL
DEPTH OF SOIL IN FEET
PORE-SPACE REPRESENTING THE WATER CONTENT WHICH WOULD RESULT IF DRAINAGE WERE PREVENTED AND ALL OF THE SOIL AIR WERE REPLACED BY WATER
MOISTURE EQUIVALENT
IRRIGATION
PLOT D BEFORE
PLOT D AFTER
PLOT B BEFORE IRRIG.
PLOT B AFTER
LEGEND
BROKEN LINE — — — PLOT B (2-5" IRRIGATIONS)
SOLID LINE ——— PLOT D (4-6" IRRIGATIONS)
DOTTED LINE ..... MOISTURE EQUIVALENT

FIG. 7.—Graphs showing the comparison of water content before and after irrigation, moisture equivalent, and pore space of soils of plots B and D, Davis, Cal. Each water-content curve in plot B is the average of 14 borings; in plot D, of 28 borings.

MAXIMUM CAPILLARY CAPACITY OF DISTURBED SOILS AND SOILS IN PLACE

That the results of standard laboratory determinations of maximum capacity of soils do not accurately represent capillary capacities of soils in place is generally recognized. Widtsoe (*12*) determined the maximum capillary capacity of a soil in place by studying three columns 1 foot, 2 feet, and 3 feet long, respectively. The samples were taken by driving iron cylinders into the soil, thus getting it almost in its natural condition. By means of three independent linear equations, the effect of the special "lifting power" exerted by the end of each soil column was eliminated. It was found by this procedure that 28.4 per cent of the total water held in the 1-foot column was retained by this special force, which does not exist in ordinary field soils. The maximum capillary capacity thus

found was 26.8 per cent and the maximum quantity of water found in the soil after irrigation was 24.0 per cent.

It is highly desirable to establish, if possible, a relation between some of the more generally used soil constants (3) and the maximum field capacity of the soil. An attempt has therefore been made to compare the maximum capillary capacity as determined in the laboratory to the field capacity. The laboratory determinations were made by the use of brass cylinders 2 inches in diameter and 12 inches long, having perforated bottoms, which were filled on the Bowman soil compactor, placed in water to a depth of 10 inches overnight, and drained for 24 to 48 hours.

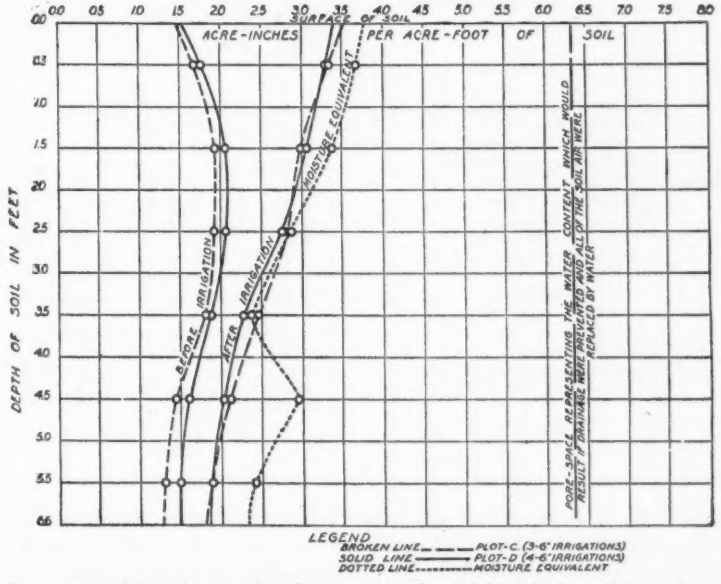
ACRE-INCHES PER ACRE-FOOT OF SOIL
SURFACE OF SOIL
DEPTH OF SOIL IN FEET
BEFORE IRRIGATION
AFTER IRRIGATION
MOISTURE EQUIVALENT
PORE-SPACE REPRESENTING THE WATER CONTENT WHICH WOULD RESULT IF DRAINAGE WERE PREVENTED AND ALL OF THE SOIL AIR WERE REPLACED BY WATER
LEGEND
BROKEN LINE — PLOT C (3-6' IRRIGATIONS)
SOLID LINE — PLOT D (4-6' IRRIGATIONS)
DOTTED LINE — MOISTURE EQUIVALENT

FIG. 8.—Graphs showing the comparison of water content before and after irrigation, moisture equivalent, and pore space of soils of plots C and D, Davis, Cal. Each water-content curve in plot C is the average of 21 borings; in plot D, of 28 borings.

The results reported in Table IX include the hygroscopic water contained in the air-dry sample used.

The surface foot of the first group of soils listed in Table IX was no doubt fully saturated by the large amounts of water applied. The quantities held per foot of soil vary from 2.58 in the Griffes tract to 3.67 in the Geer tract. The ratio of the amount held in the laboratory to that held in the field varies from 1.53 to 2.10 and has a mean of 1.78 ± 0.06. The probable error of a single observation is ± 0.19 inch per foot. Although the second group of soils was irrigated more moderately, the average unit application was 8.11 inches, which is much more than 1 foot of soil can retain. Therefore the amounts held

should closely approach the maximum capillary field capacity. The higher average ratio found, 1.98±0.14, is due in part to the fact that the soils are heavier and therefore undergo greater change in structure when disturbed. The probable error of the ratio for a single observation is ±0.24.

TABLE IX.—*Comparison of the maximum capillary capacities of disturbed soils as determined in the laboratory with the maximum quantities of water contained after irrigation by the surface foot of the soils in place*

Degree of irrigation.	Name and location of tract.	Maximum in laboratory (inches per foot of soil).	Maximum after irrigation (inches per foot of soil).	Ratio, laboratory to field capacity.	Pore space of soils in place (inches per foot of soil).	Ratio, laboratory capacity to pore space.
						Per cent.
Heavy	Wigno, Los Molinos	4.00	2.62	1.53	7.10	56.4
	Griffes, Woodland	4.90	2.58	1.90	6.66	73.5
	Bundy, Los Molinos	6.28	3.50	1.79	6.31	99.5
	Hofhenke, Los Molinos	5.02	3.27	1.54	6.32	79.5
	Hughson, Woodland	5.61	2.87	1.95	6.66	84.2
	Huartson, Gridley	5.93	2.92	2.03	6.06	98.0
	O'Hair, Orland	5.88	3.14	1.87	6.10	96.4
	Geer, Los Molinos	4.83	3.67	1.32	6.36	76.0
	University Farm, Davis	6.52	3.10	2.10	6.32	103.0
	Average	5.44	3.07	1.78 ±0.06	6.43	85.4
Medium	Guile, Woodland	7.64	4.00	1.91	5.78	132.0
	Jackson-Woodward, Woodland	6.97	4.04	1.72	6.42	108.0
	Beck, Woodland	6.85	2.97	2.30	6.18	111.0
	Average	7.15	3.67	1.98 ±0.14	6.13	117.0

In Table X comparisons are made between the maximum quantities contained after irrigation by the first- and second-foot sections of soil and their moisture equivalents (3). Examination of the ratio of the moisture equivalent to the maximum quantity of water held after irrigation indicates the former to be slightly larger than the latter. The averages of this ratio, 1.13±0.02 and 1.12±0.02, for the first- and second-foot sections, respectively, of the heavily irrigated soils show remarkable agreement.[1] The increase in the average ratio of the second group from 1.20±0.06 to 1.38±0.02 is due to the fact that the heavier soils of the second group were not so fully wetted in the second foot. Likewise, the average ratio 1.48±0.05 for the third group is high because of

[1] The ratio of the moisture equivalent to the moisture content, one week after irrigation, of various soils of Montana and Idaho has been determined by Prof. S. T. Harding, of the University of California, while connected with irrigation investigations of the United States Department of Agriculture. The moisture equivalents of the soils on which Mr. Harding worked varied from 14.9 to 29.3. His results show an average ratio of 1.17 in the surface foot of soil, of 1.16 in the upper 2 feet, and of 1.08 in the upper 5 feet. Considering the wide range of soils studied and the many variations in other conditions, these ratios agree very well with the ones above presented.

the difficulty in wetting these compact impervious soils. This high ratio may also be the result of difference in volume weight between the soil in the field and in the perforated cup of the centrifuge.[1] The probable error of a single comparison in the first group is ±0.06 for both foot sections; for the second group ±0.12 in the first foot and ±0.04 in the second; for the third group it is ±0.11.

TABLE X.—*Comparison of the maximum quantities of water contained after irrigation by the first- and second-foot sections of soil in place with their moisture equivalents*

SOILS HEAVILY IRRIGATED

Name of tract.	First foot of soil.				Second foot of soil.			
	Moisture equivalent.		Maximum quantity of water after irrigation (inches per foot of soil).	Ratio, moisture equivalent to maximum quantity after irrigation.	Moisture equivalent.		Maximum quantity of water after irrigation (inches per foot of soil).	Ratio, moisture equivalent to maximum quantity after irrigation.
	Per cent.	Inches per foot of soil.			Per cent.	Inches per foot of soil.		
Wigno	24.18	3.18	2.62	1.21	24.45	3.22	2.73	1.18
Griffes	20.64	2.98	2.58	1.15	21.22	3.06	2.57	1.19
Hundy	28.63	4.48	3.50	1.28	26.92	4.20	3.62	1.16
Hofhenke	22.12	*a* 3.45	3.27	1.05	22.12	3.45	3.19	1.05
Hughson	22.10	3.21	2.87	1.12	21.70	3.15	2.94	1.07
Huartson	21.46	3.38	2.92	1.16	22.10	3.48	2.90	1.20
O'Hair	23.87	3.18	3.14	1.01	21.70	2.89	2.31	1.15
Geer	24.75	3.78	3.67	1.03	26.71	4.08	3.86	1.06
University farm	23.88	3.67	3.25	1.13	21.90	3.37	3.10	1.09
Average	23.52	3.48	3.09	1.13±0.02	23.20	3.43	3.06	1.12±0.02

SOILS MODERATELY IRRIGATED

Guile	24.18	4.07	4.00	1.02	28.74	4.83	3.34	1.44
Jackson-Woodard	30.31	4.58	4.04	1.13	31.65	4.79	3.52	1.36
Beck	25.68	4.07	2.97	1.37	25.18	3.99	2.84	1.40
Wright	27.72	4.98	3.83	1.30	27.54	4.96	3.76	1.32
Average	26.97	4.42	3.71	1.20±0.06	28.28	4.64	3.36	1.38±0.02
Purdy	21.02	4.14	3.03	1.37				
Tuttle	19.30	4.03	3.09	1.34				
Willows' experimental tract, plots 3 and 4	19.70	4.14	2.40	1.72	The impervious nature of these soils prevented the irrigation water from wetting the second foot; therefore comparisons are not made.			
Willows' experimental tract, plots 6 and 7	22.59	4.75	2.97	1.60				
Willows' experimental tract, plots 11 and 12	20.70	4.35	2.91	1.50				
Average	20.66	4.28	2.88	1.48±0.05				

a Moisture-equivalent sample for first foot determined on soil from second foot.

The comparisons made in Table X suggest that the moisture equivalent may be made a means of judging the maximum capillary capacity

[1] That the volume weights of these clay soils are higher in the field than in the ordinary air-dry condition in the laboratory has been determined beyond reasonable doubt. If the same relative condition exists between the volume weights in the field and in the perforated cups of the centrifuge the increase of the ratio with increase of fineness of soil would be readily accounted for. However, volume-weight determinations were not made upon the soils after rotation in the centrifuge; nor have any such determinations been made, so far as known to the writer.

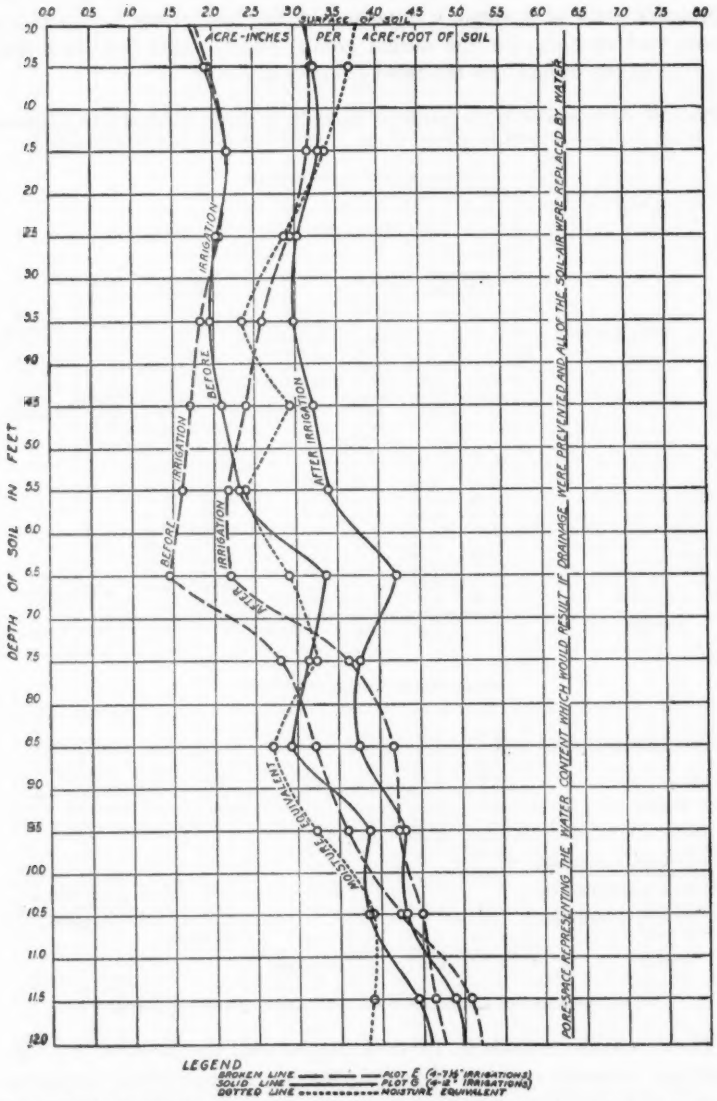
ACRE-INCHES PER ACRE-FOOT OF SOIL
SURFACE OF SOIL
DEPTH OF SOIL IN FEET
BEFORE IRRIGATION
AFTER IRRIGATION
BEFORE IRRIGATION
AFTER IRRIGATION
MOISTURE EQUIVALENT
PORE-SPACE REPRESENTING THE WATER CONTENT WHICH WOULD RESULT IF DRAINAGE WERE PREVENTED AND ALL OF THE SOIL AIR WERE REPLACED BY WATER
LEGEND
BROKEN LINE — PLOT E (4-7½" IRRIGATIONS)
SOLID LINE — PLOT G (10-12" IRRIGATIONS)
DOTTED LINE ..... MOISTURE EQUIVALENT

FIG. 9.—Graphs showing the comparison of water content before and after irrigation, moisture equivalent, and pore space of soils of plots E and G, Davis, Cal. Each water-content curve is the average of 28 borings.

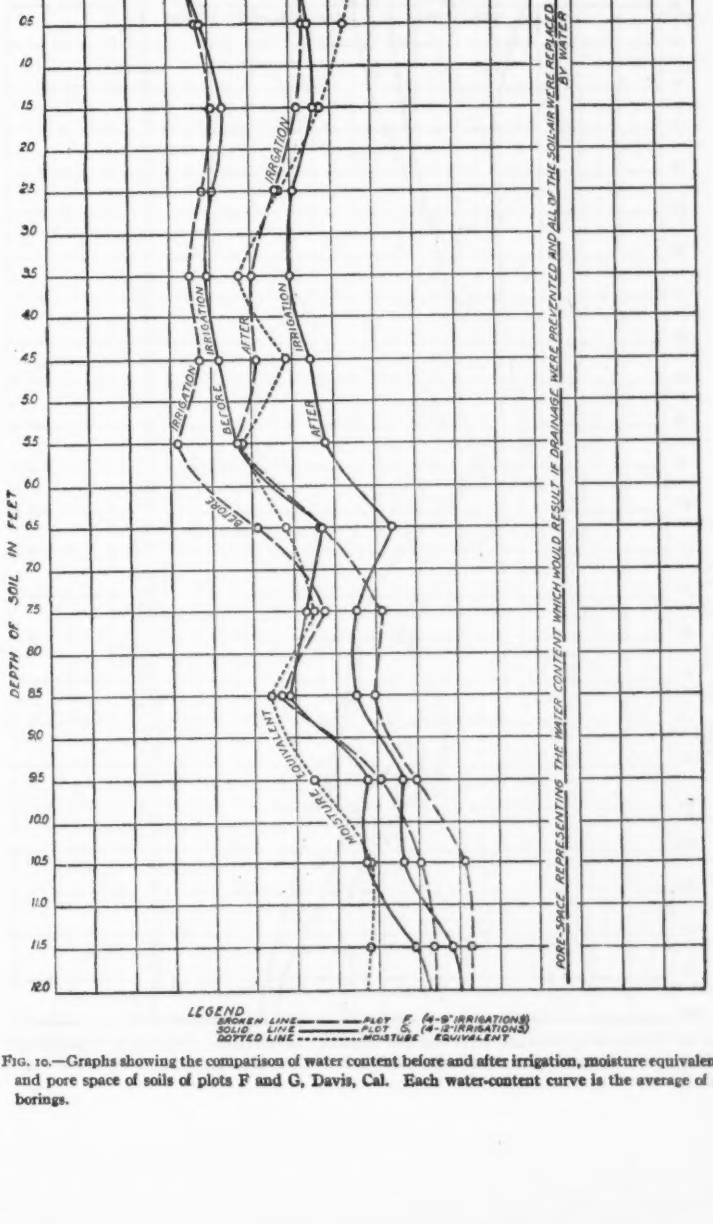
SURFACE OF SOIL
DEPTH OF SOIL IN FEET
IRRIGATION
BEFORE IRRIGATION
AFTER IRRIGATION
BEFORE
AFTER
EQUIVALENT MOISTURE
PORE-SPACE REPRESENTING THE WATER CONTENT WHICH WOULD RESULT IF DRAINAGE WERE PREVENTED AND ALL OF THE SOIL-AIR WERE REPLACED BY WATER
LEGEND
BROKEN LINE —— —— PLOT F (4-8" IRRIGATIONS)
SOLID LINE —— —— PLOT G (4-12" IRRIGATIONS)
DOTTED LINE ..... MOISTURE EQUIVALENT

FIG. 10.—Graphs showing the comparison of water content before and after irrigation, moisture equivalent, and pore space of soils of plots F and G, Davis, Cal. Each water-content curve is the average of 28 borings.

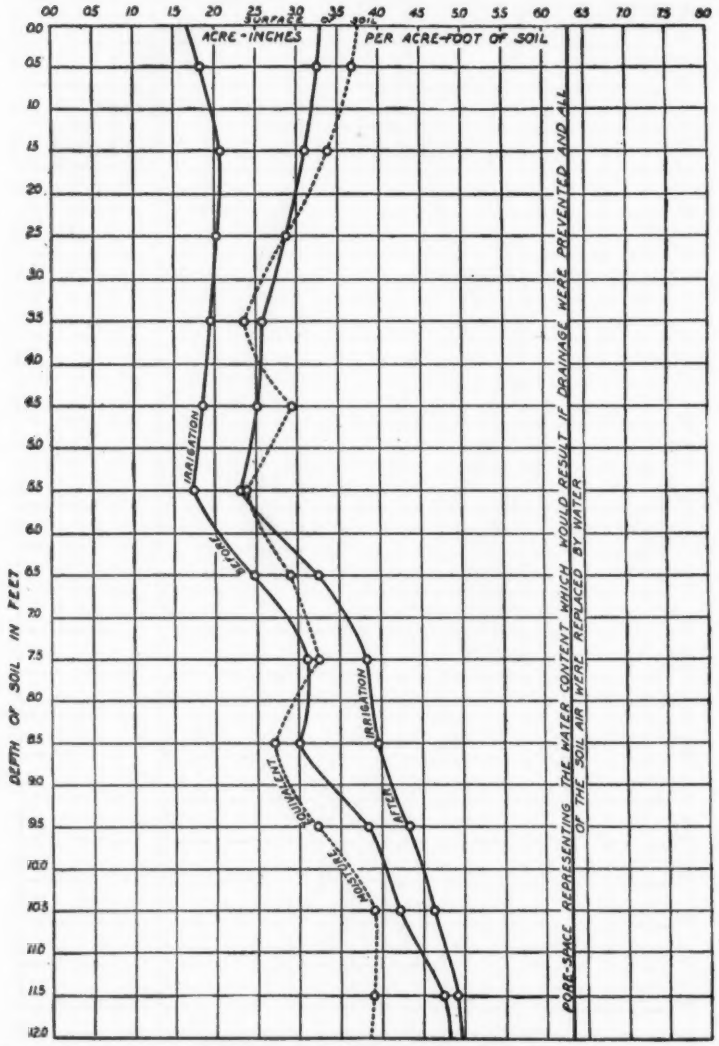
ACRE-INCHES PER ACRE-FOOT OF SOIL
DEPTH OF SOIL IN FEET
IRRIGATION
EVAPORATION
IRRIGATION
EVAPORATION
HYGROSCOPIC
PORE-SPACE REPRESENTING THE WATER CONTENT WHICH WOULD RESULT IF DRAINAGE WERE PREVENTED AND ALL OF THE SOIL AIR WERE REPLACED BY WATER

FIG. 11.—Graphs of water content before and after irrigation, moisture equivalent, and pore space of soils. Each water-content current is the average of 6 plots, B to G, for 1913, 1914, and 1915, and the average of 147 borings.

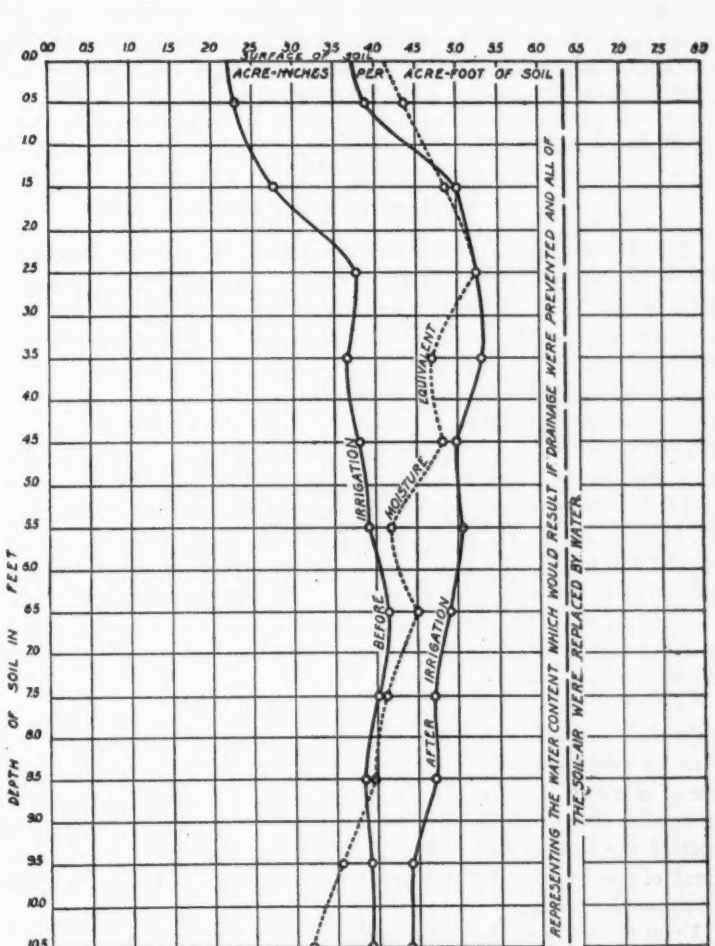
SURFACE OF SOIL
ACRE-INCHES PER ACRE-FOOT OF SOIL
DEPTH OF SOIL IN FEET
IRRIGATION
MOISTURE
EQUIVALENT
BEFORE IRRIGATION
AFTER IRRIGATION
PORE-SPACE REPRESENTING THE WATER CONTENT WHICH WOULD RESULT IF DRAINAGE WERE PREVENTED AND ALL OF THE SOIL-AIR WERE REPLACED BY WATER

FIG. 12.—Graphs of water content before and after irrigation, moisture equivalent, and pore space of soils. Each water-content curve is the average of 28 borings on plot H (four 15-inch irrigations) for 1913, 1914, and 1915.

of soils in place. Though definite conclusions from so few correlations are not warranted, it seems that the moisture equivalent represents more nearly the maximum capillary capacity of the soil in place than do the ordinary laboratory determinations upon the disturbed soil, both in point of accuracy and of absolute value.

PART II.—A NEW METHOD OF DETERMINING THE VOLUME WEIGHTS OF SOILS

RUBBER-TUBE METHOD

In order to ascertain accurately by means of moisture determinations the volume of irrigation water which a given volume of soil absorbs and retains, it is obviously necessary to know with a fair degree of accuracy the volume weight of the soil in place. It was believed early in these studies and has since been verified that the ordinary method of determining volume weight of samples of disturbed soil could not be relied on. The use of an iron cylinder to be driven into the soil for determining its volume weight in place was considered. It was concluded that this method was unsatisfactory because of the tendency of the soil below the cylinder to become compacted and thus be driven ahead of, instead of into, the cylinder, and because of the time and expense involved in taking very many samples to the depths which must be considered in the soils of the arid regions. The first objection applies especially to the use of cylinders of small diameter, such as the King soil tube, and the second to larger tubes, with which the first objection may be measurably overcome.

The need of devising a new method which would overcome these objections seemed sufficiently urgent to warrant attention. The soil samples used for making moisture determinations were secured by the use of a 2-inch auger of the post-hole type. The diameter of the tip or cutting edge of the bowl of the auger used was slightly greater than that of the base, a fact which suggested that practically no displacement of soil by lateral thrust or compacting ahead of the auger would be caused by boring.

Upon the basis of these assumptions it was necessary only to devise a means of accurately measuring the volume of the hole made by a 6-foot boring in order to get a satisfactory measure of the volume weight of the soil, since the total amount of soil taken from the hole 2 inches in diameter and 6 feet deep could very conveniently be taken to the laboratory, dried, and weighed. Various methods of measuring the volume of the auger hole were considered. It was attempted to measure the diameter of the hole at different depths by means of calipers and thus compute the volume, but this proved unsatisfactory. Finally it was conceived that an accurate measurement of the volume could be obtained by inserting a very thin-walled elastic rubber tube into the auger hole

and filling it with water from a graduated cylinder. A special rubber tube having a diameter of 2¼ inches and a length of 6½ feet was secured and determinations were made of the volume weight as follows: Borings were made with the 2-inch auger above described to a depth of 1 foot, the soil being placed on an oilcloth and then into a suitable bag. The closed spherical end of the rubber was then forced into the hole upon the rounded end of a pole 1½ inches in diameter. Water was poured from a full 1,000-c. c. graduate cylinder into the tube until it was filled to a point flush with the surface of the soil.[1]

The water was then drawn out of the tube by means of a small pump, after which the tube was taken out of the hole and dried. Then the borings were continued to a depth of 2 feet and the volume of the hole again determined, the volume of the section from 1 to 2 feet being obtained by difference. This process was continued until the six upper 1-foot sections had been studied. The materials used are shown in Plate 1, A. The soils were oven dried and weighed. The volume of the rubber tube, 200 c. c., was taken into account in the determination of the total volume occupied by the undisturbed soil.

Laboratory volume-weight determinations were made upon the disturbed soil as follows: Brass tubes 2 inches in diameter and 10 inches long were filled with thoroughly pulverized air-dry soil on the Bowman compactor. The weight of the soil was corrected for hygroscopic moisture, and the volume of the tube was computed and also determined by filling it with water.

The volume weights of the upper 6 feet observed by the two methods are set forth in Table XI, in the last column of which the percentage decrease in volume weight caused by disturbing the soil is given. These percentages show great variation, which was not unexpected. The volume weight of the clay soil of the Willows experimental tract was decreased nearly 23 per cent by being disturbed, while that of Wigno tract (fine sandy loam) was increased 15 per cent. The most striking factor brought out by the study of the volume weight of the soil in place as presented in Table XI is the fact that the coarse-textured soils have in general much lower volume weights than the fine-textured ones, a relation just the reverse of that which is generally believed to exist between texture and volume weight.

[1] In using a 6-foot rubber tube for the first, second, and third foot sections, some difficulty was experienced in determining this point accurately. This difficulty could be overcome by providing several tubes of different lengths. For example, if it is desired to make a volume-weight determination of each foot section to a depth of 6 feet, the first tube used should be about 16 inches in length, the second 28, the third 40, and so on.

TABLE XI.—*Volume weights of different soils as determined (1) upon disturbed soil by the ordinary laboratory methods, and (2) upon soil in place by the rubber-tube method*

Name and location of tract.	Volume weight.		Percentage decrease in volume weight caused by disturbing the soil.
	By laboratory method upon disturbed soil.	By rubber-tube method with soil in place.	
University Farm, Davis	1.200	1.280±	6.3
Hughson, Woodland	1.220	1.210±0.015	−1.0
Jackson–Woodward, Woodland	1.135	1.257± .007	8.8
Guile, Woodland	1.185	1.398± .002	15.2
Purdy, Willows	1.340	1.642± .011	18.5
Tuttle, Willows	1.380	1.741± .019	20.8
Willows experimental tract, Willows	1.350	1.750± .010	22.9
Wigno, Los Molinos	1.280	1.112± .019	−15.0
Bundy, Los Molinos	1.200	1.289± .001	6.8
Geer, Los Molinos	1.350	1.272± .013	− 6.0

OTHER METHODS USED

In order to check the above method, further studies were conducted cooperatively with Prof. Charles F. Shaw, (3) of the Division of Soil Technology, University of California, the work being done chiefly by the paraffin-immersion method employed by him at the Pennsylvania Agricultural Experiment Station.[1] Further volume-weight determinations were also made by use of an iron cylinder 6 inches in diameter. The procedure in the paraffin-immersion method is outlined below: A hole, 3 feet wide and 6 feet long, was excavated to a depth of 5 feet by use of pick and shovel. At one end steps were made in the soil for convenience in getting into and out of the hole. One side of the excavation was carefully smoothed and plumbed. From this side two sections of soil 1 foot apart and of approximately 1 foot in cross section were excavated, thus leaving a vertical column 1 foot square and 5 feet high, having three sides exposed, as represented in figure 13. The top of this column was carefully smoothed by means of a spatula, putty knife, and trowel. The fourth side of the column was cut from its base to a depth of 6 inches with a spatula; and at the same depth below the surface of the column the spatula was inserted horizontally from the three exposed sides and thus a ½ cubic-foot sample, 1 foot square and ½ foot long, representing approximately the upper 6 inches of soil, was severed from the 5-foot column. The sample was placed upon the platform, as shown in Plate 1, B, cut into four cubes of approximately equal size, the best three of which were used in determining the volume weight.

[1] For a description of the method proposed by Prof. Shaw, see BROWN, B. E., MACINTIRE, W. H., and CREE, W. F. COMPARATIVE PHYSICAL AND CHEMICAL STUDIES OF FIVE PLATS, TREATED INDEPENDENTLY FOR TWENTY-EIGHT YEARS. *In* Penn. Agr. Exp. Sta. Ann. Rpt., 1909–10, p. 96–97. 1910.

Each sample was placed on a weighed wire-mesh support, weighed upon a solution balance, dipped into warm paraffin until fully coated (usually three or four times), reweighed, and placed into a large desiccator of known volume.[1]

The desiccator containing the soil, paraffin coating, and wire-mesh support was filled with water from a 1,000-c. c. graduate cylinder and the volume of the soil, paraffin, etc., determined by displacement. From the known weights of the paraffin and wire-mesh support their volumes were computed, using 0.9 as the density of paraffin and 8.0 as the density of the wire. After the volume measurement the cubes of soil were broken and a 200-gm. sample taken for the determination of the moisture content. The results are presented in the last column of Table XII.[2]

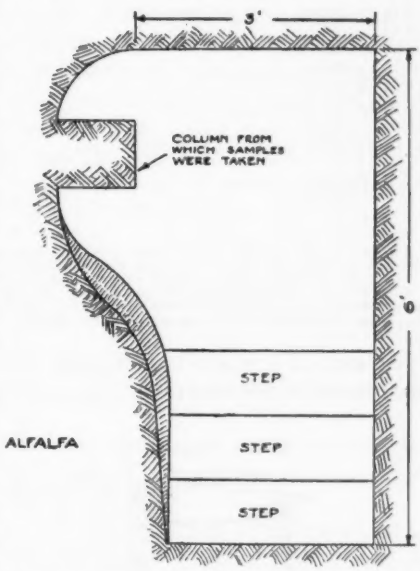

FIG. 13.—Diagram showing plan of excavation for the determination of the volume weight of soil by means of the paraffin-immersion method.

The results presented in column 3 of Table XII were obtaind by the use of a specially prepared iron cylinder, having a diameter of 6 inches, which could be driven into soils of ordinary compactness only with great difficulty. It was therefore not attempted to drive it into this very compact clay; but the top of a column of soil having a circular cross section of about 8 inches in diameter was carefully smoothed and leveled, after which two spatulas were inserted horizontally into the column. The iron cylinder was placed vertically upon the column, as indicated in figure 14. The column was trimmed very carefully with a trowel until its diameter was slightly greater than that of the cylinder. The weight of the cylinder, aided by very light tapping, caused it to move slowly down over the soil column.

[1] The cover of the desiccator used has a 1-inch diameter opening in its center, thus making it possible to measure the desiccator volume accurately.

[2] The probable errors were determined by use of Peter's Formula $Rm = \frac{0.845 \Sigma V}{n\sqrt{n-1}}$. Where Rm = the probable error of the arithmetic mean of n determinations, and ΣV = the sum of the differences between the arithmetic mean and each determination. In this case $n = 3$. It is recognized that where n is so small the formula is not strictly accurate.

TABLE XII.—*Volume weights of Tehama clay, Willows experimental tract, Willows, as determined (1) upon the disturbed soil by the ordinary laboratory method, (2) upon the soil in place, (a) by the rubber-tube method, (b) by the iron-cylinder method, and (c) by the paraffin-immersion method*

Depth of soil.	Laboratory method on disturbed soil.[a]	Rubber-tube method with soil in place.[b]	Iron-cylinder method with soil in place.[c]	Paraffin-immersion method with soil in place.
2 to 7 inches	.....	.....	1.632	1.671±0.004
8 to 13 inches	.....	.....	1.721	1.702± .008
15 to 20 inches	.....	.....	1.781	1.784± .007
22 to 27 inches	.....	.....	1.750	1.802± .002
28 to 33 inches	1.380±0.007	.....	1.828	1.802± .007
35 to 40 inches	.....	.....	1.780	1.792± .000
42 to 47 inches	.....	.....	1.732	1.757± .012
48 to 53 inches	.....	.....	1.625	1.747± .010
54 to 60 inches	1.320± .004	.....	.....	1.541± .028
Average, 0 to 60 inches	1.350± .008	1.744±0.010	1.731	1.733± .035

[a] Laboratory determinations were made upon composite samples from only two depths; (1) from 0 to 2.5 feet, and (2) from 2.5 to 5 feet. The results given are averages of 12 determinations from each depth.
[b] Only one depth considered in rubber-tube method, 0 to 5 feet.
[c] Depths given for iron-cylinder method are almost but not strictly accurate. Total depth covered by eight samples in this method, 58 inches. Lack of rigid accuracy in depths due to slight but unavoidable loss of soil in preparing each 6-inch section for the cylinder.

As soon as it reached the spatula blades, the 6-inch column within the cylinder was severed from its base, and the end was carefully smoothed

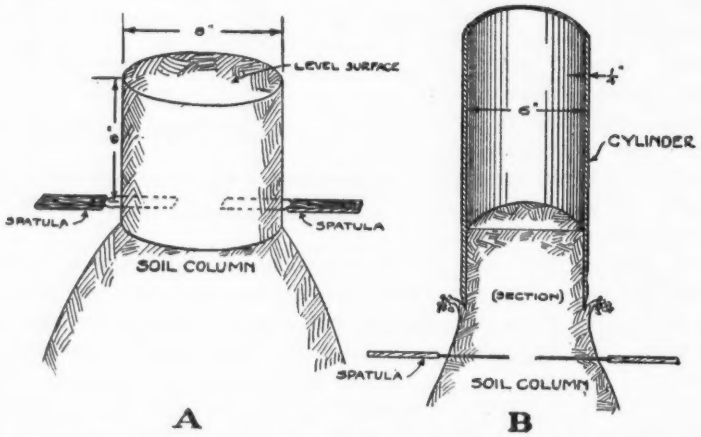

FIG. 14.—Diagram showing method used for the determination of the volume weight of soil by the use of an iron cylinder: *A*, column of soil ready for determination; *B*, cylinder being placed over the column of soil.

flush with the cylinder, after which the soil was taken out, weighed, and sampled for a moisture determination. The process was continued until eight samples had been taken. These covered a total depth of

not quite 5 feet, since some soil was lost in smoothing the column. Compacting in the cylinder was very largely, if not entirely, overcome. Measurements of the length of the column in the cylinder gave results varying from 6⅛ to 5⅞ inches. These variations are believed to be due to the difficulty found in inserting the spatula at the 6-inch point without deviating from the horizontal plane rather than to any change in structure of the soil.

Only one sample was taken at each depth; consequently probable-error calculations can not be made. Very gratifying agreement exists between the results obtained by use of the iron cylinder and those obtained by the paraffin-immersion method, as presented in Table XII. Especially is this true of the averages for the upper 5 feet, wherein the difference is entirely insignificant. Moreover, the results obtained by the paraffin-immersion method and the iron-tube method, which were secured in March, 1916, confirmed beyond doubt the correctness of the results obtained by the rubber-tube method in October, 1915, at the end of the irrigation season.

SUMMARY

(1) This paper reports some observations upon the capacities of certain soils under different conditions to retain water and also develops a new method of determining the volume weight of soils in place, representing some phases of a six-year study of the economical duty of water for alfalfa in Sacramento Valley.

A relation between the depth of water necessary to add a given percentage of moisture to a certain depth of soil of given volume weight is expressed mathematically and graphically.

The observations of capacity of soils to retain water are based on 9,584 moisture determinations in the upper 6 feet of soil, 672 in the depth from 7 to 9 feet, and 192 in the tenth to twelfth foot sections, making 10,448 in all.

Volume-weight determinations upon which the pore-space values largely depend and by which the percentages of water were converted to inches of water per foot of soil were made upon the soils in place to a depth of 6 feet.

(2) The observations indicate that percentages of pore space which are filled by the water that a soil holds immediately after irrigation increases with the increase in fineness of soil texture. Variations from 40 per cent in silt-loam soils having fine sandy-loam subsoils, 51 per cent in the silt loams, 58 per cent in the clay loams, to 66 per cent in the clay soils have been noted.

(3) The ratio of the maximum capillary capacities of soils, as determined in a 10-inch tube in the laboratory, to that of the same soils observed in the field after irrigation varied from 1.78 ± 0.06 to 1.98 ± 0.14.

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(4) Correlations between the moisture equivalent and the maximum amounts of water found after irrigation show a gratifying agreement and suggest that the moisture equivalent might be made a basis of judging maximum capillary capacities.

(5) A new method of determining volume weight of soil in place which is simple of manipulation and inexpensive is described. The results of the new method of determining the volume weight of clay-loam soil, as checked by a paraffin-immersion method first used by Prof. Charles F. Shaw and by the use of an iron tube, were subject to an error of less than 1 per cent.

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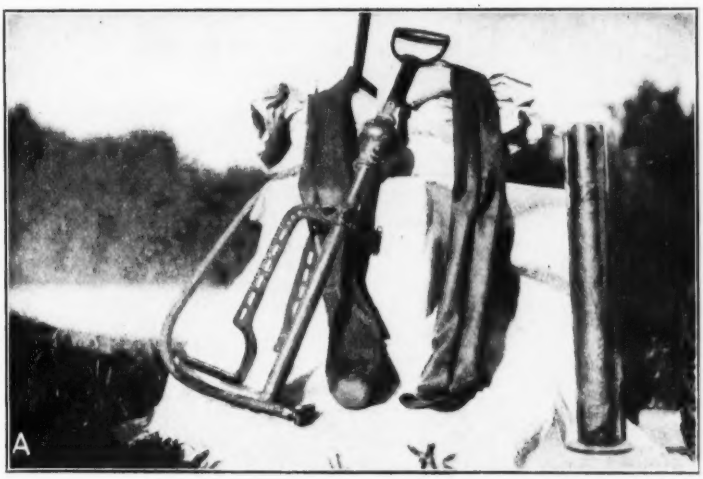
PLATE 1

A.—Apparatus used for the determination of the volume weight of soils in place by the rubber-tube method.

B.—Apparatus used for the determination of the volume weight of soils in place by the paraffin- immersion method.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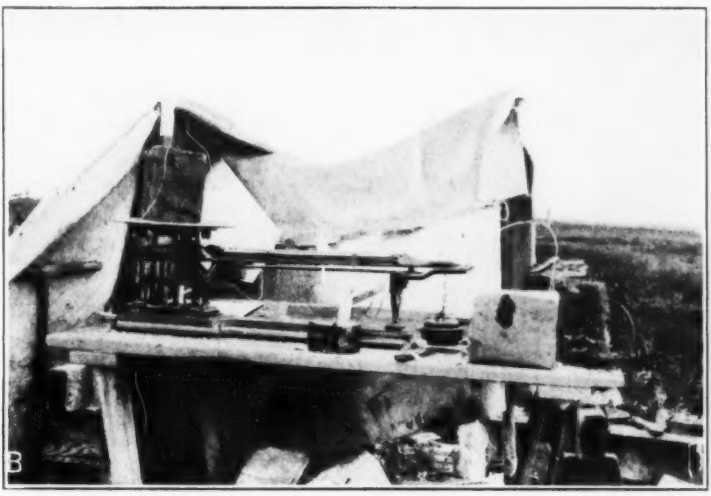
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SOME STONEFLIES INJURIOUS TO VEGETATION

By E. J. NEWCOMER

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INTRODUCTION

Stoneflies (Plecoptera) are not ordinarily classed among the insects injurious to plant life. Indeed, a study of the mouth parts of several species has shown them to be more or less rudimentary,[1] so that, while they are of the biting type, they are not capable of being used to inflict injury upon plant growth. John B. Smith says[2] that adult stoneflies do no feeding upon living plants, so far as known. The writer has been much interested, therefore, in studying the habits of several of the western species of the genus Taeniopteryx (*Taeniopteryx pacifica* Banks, *T. pallida* Banks, and *T. nigripennis* Banks), which are equipped with well-developed mouth parts, and which feed upon the buds and leaves of plants. One species in particular, *T. pacifica*, has proved to be of considerable economic importance in the Wenatchee Valley, in central Washington. While it has not been possible to make detailed life-history studies, or to work out satisfactory control methods, it has been thought advisable to publish a short paper on the subject, owing to the unusual habits of these species.

OCCURRENCE

When the writer arrived at Wenatchee, Wash., in May, 1914, he was shown injuries to foliage and fruit which had been caused by an insect known locally as the "salmon fly." Unfortunately the insects had all disappeared. However, the writer recalled an early experience in the Yellowstone Park where insects known as "salmon flies" were plucked from one's clothing or from the adjacent foliage and used as bait in catching salmon trout from the Yellowstone River. These insects were a species of stonefly, and the descriptions given the writer of the insect at Wenatchee indicated that it was also a stonefly. During the following two years (1915 and 1916) ample opportunity was afforded for studying the habits of the salmon fly, which proved to be a stonefly, and which has been identified by Mr. Nathan Banks, formerly of the Bureau of Entomology, as *Taeniopteryx pacifica*.

[1] SMITH, Lucy W. THE BIOLOGY OF PERLA IMMARGINATA SAY. *In* Ann. Ent. Soc. Amer., v. 6, no. 2, p. 203–212, illus., pl. 23. 1913.

[2] SMITH, John B. INSECTS OF NEW JERSEY. *In* Ann. Rpt. N. J. State Mus., 1909, p. 15–880, illus. 1910.

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In 1915 the stoneflies appeared early in March, becoming common by the middle of the month. They were observed flying about on warm days, and examinations of the various fruit trees showed that the flies were resting on the twigs and branches in some numbers. In 1916 the flies did not appear until March 22, as the season was late, but on this date, which was the first warm spring day, they were very numerous. At this time most of the fruit buds were beginning to swell. The flies were abundant during both seasons for three or four weeks, after which they disappeared. The distribution of the species is not well known. The type specimens came from Pullman, Wash., which is 160 miles southeast of Wenatchee, and it is probable that this insect occurs throughout the arid region of the Northwest, wherever there are streams of sufficient size for the nymphs.

HABITS

The economic importance of this stonefly lies in its habit of eating the foliage and of biting into the buds of fruit trees. When the flies first appear the fruit buds are beginning to push out, and the flies eat large holes in them, frequently destroying them entirely (Pl. 2, B). Even where the injury is not so severe the blossoms and leaves developing from these buds are deformed and ragged (Pl. 2, A). The ovary of the blossom is very often injured, resulting in deformed fruit. Later the insects feed on the calyces and corollas of the blossoms, on the young fruit (Pl. 3, B), and on the tender foliage (Pl. 3, A,). Apricots, peaches, and plums are most seriously injured. Their buds are soft and tender, and the stoneflies have no difficulty in feeding on them. Cherries are not so noticeably injured, the buds being harder and the young foliage being sticky. The damage to apples and pears is negligible, as their buds are tougher and they blossom later.

The insects may be found commonly lying lengthwise along the twigs (Pl. 2, C), and sometimes on the larger branches. Frequently, by jarring the branches, hundreds of them will be dislodged, and they will drop to the ground or fly awkwardly to other trees. They do not appear to feed when the weather is cold or cloudy, but during the warmer parts of sunny spring days they are quite actively moving about and feeding on the buds or young foliage. Often they will be found with their heads half buried in the holes they have eaten in the buds, their long, filamentous antennæ waving continually. If slightly disturbed, they will stop feeding and remain motionless, or slide around to the other side of the twig. Both sexes have been found in the trees, and mating has been observed to take place here. It is evident that this habit of feeding in fruit trees is an acquired one, since the early stages of the insect are passed in the natural streams, and it was undoubtedly abundant before fruit trees were ever planted in the valley. The native vegetation, especially that along the streams, was carefully examined,

and the stonefly was observed feeding to some extent on the leaves of the wild rose, on the leaves and catkins of the willows (*Salix* spp.), and on the leaves of the wild cherry (*Prunus emarginata* and *P. demissa*) and alder (*Alnus tenuifolia*), and also on the cultivated elm (*Ulmus americana*). The insect seems to prefer the rosaceous plants, although it does not confine its feeding to them.

The injury caused by this stonefly was quite noticeable, especially in the lower part of the Wenatchee Valley, known as the Rock Island district, where there are extensive orchards near the Columbia River. Many growers here said that it was very seriously damaging their apricots and peaches, necessitating the discarding of much of the fruit.

CONTROL

Owing to other work, it was not possible to carry out any extensive experiments in the control of the stonefly. It was noted in 1915, however, that plum trees which had been sprayed with crude-oil emulsion and nicotine sulphate for aphids were not as badly injured as those not sprayed. Several growers reported spraying their trees with nicotine sulphate and soap, with varying success. On April 3, 1916, an apricot orchard was examined, part of which had been sprayed about April 1 with lead arsenate at the strength ordinarily used for the codling moth on apples (2 pounds of lead arsenate to 50 gallons of water). At this time the buds were beginning to show green. A number of buds were examined and counted on both sprayed and unsprayed trees. On the latter trees 60 per cent of the buds were injured, while on the former only 24 per cent were injured, and it is probable that much of this latter injury was done before the trees were sprayed, as the flies had been numerous for over a week. It seems probable that in order to protect the trees completely two applications of spray would be necessary, as the buds are developing rapidly at this time. The first application would naturally be put on as soon as the flies appear, and the second either just before blossoming or just as the petals are falling.

LIFE HISTORY

At the time the stoneflies were abundant several of the smaller streams flowing into the Columbia River near Wenatchee were examined, but no emerging flies were found. The shores of the Columbia River, which at Wenatchee is a large, swiftly flowing stream about one-fourth of a mile wide, were then examined, and the flies were found emerging in large numbers. Thousands of cast nymphal skins (Pl. 3, C) were strewn along the shore from the water's edge to 10 or 15 feet above it. Hundreds of crippled flies were scrambling about over the rocks, but few perfect ones were seen, as these evidently fly away as soon as their wings are sufficiently dried. In the shallow water under the larger stones the nymphs were found, most of them just ready to emerge.

As mating was observed in the orchards, and as the bodies of most of the female stoneflies taken here contained eggs, it is evident that the females must return to the river after feeding to deposit their eggs. These eggs hatch in the water, and the nymphs develop slowly, the adults emerging in the spring as soon as the weather becomes warm. Whether the nymphs complete their development in a single year, or require two years or more, is not known.

DESCRIPTIONS OF STAGES

EGG.—Oviposition was not observed; nor were eggs found in the water; but eggs dissected from the body of the female were approximately spherical and about 0.2 mm. in diameter.

NYMPH (Pl. 3, C).—The full-grown nymph is about 10 mm. long, exclusive of the antennæ and cerci. The prothorax and abdomen are dull, dark brown, the head is a lighter brown, the eyes black, and the mesothorax, metathorax, and all appendages a very light brown. The filamentous antennæ are about 6.5 mm. long and the abdominal cerci about 8 mm. long. The legs are fringed with long hairs. No gills were present on the specimens collected, which were just ready to emerge and may have lost them.

ADULT (Pl. 3, C; Pl. 4, A).—The original description of the adult is given herewith:

Head dull black; antennæ brown; prothorax dull black, anterior margin, and usually the lateral margins, narrowly reddish; base of mesothorax reddish, rest of body black; legs yellow-brown, knees rather darker. Wings dull hyaline, without marks, or an indistinct cloud near the middle, hind pair hyaline, veins brown. Prothorax rather broader than long, a transverse sulcus in front, on the disk are scattered small flat tubercles or scars; second joint of tarsi as long as first, tips of tibiæ with a pair of minute spines; ventral plate of the female is nearly semicircular. Wings long, slender, subcostal with several cross-veins to margin near tip, and a few near base, radial sector with but one fork beyond the anastomosis, the vein from the discal cell arises near the radial sector, pterostigmatic region long, with but one cross-vein.

Length to tip of wings, 12 mm.

Pullman, Wash., April (C. V. Piper, R. W. Doane).[1]

DESCRIPTION OF MOUTH PARTS

Since the structure of the mouth parts determines the economic importance of an insect of this type, a detailed description of these will not be out of place here.

ADULT (PL. 4)

LABRUM.—Subquadrate, somewhat broader than long, sparsely covered with setæ; sides convex and heavily chitinized; distal margin slightly concave.

MANDIBLES.—Subtriangular, the outer margin slightly rounded, the cutting edge provided with a series of strongly chitinized teeth, which are unlike on the two mandibles. The right mandible has a sharply pointed tooth at the outer edge, behind which are three bladelike teeth and a protruding grinding edge. The left mandible has a row of three sharply pointed teeth, behind which are two bladelike teeth, the second being serrate, and a grinding edge.

MAXILLÆ.—Of the usual biting type. Galea digitiform, lacinia tapering, provided distally with two chitinous teeth, one longer and heavier than the other, and with a row of spines along the inner margin. Palpus four-jointed, covered with many setæ.

[1] BANKS, Nathan. NEW GENERA AND SPECIES OF NEARCTIC NEUROPTEROID INSECTS. *In* Trans. Amer. Ent. Soc., v. 26, no. 3, p. 244. 1900.

LABIUM.—Rather simple. Glossæ small and tapering; paraglossæ larger, thumb-like; both provided with long and short spines. Palpi three-jointed; a distinct tactile surface on the inner side of the tip, covered with short spines.

NYMPH

The nymphal mouth parts are practically identical with those of the adult, with the exception of the mandibles. The teeth of the latter, particularly the left mandible, are somewhat blunter, and the grinding edge of the left mandible is provided with a row of stout spines.

OTHER SPECIES

On May 31, 1915, a trip was taken into the mountains back of Wenatchee, and there, in the pine woods at an elevation of 3,000 feet, two distinct species of stoneflies were found feeding on the native vegetation along the banks of a swiftly flowing stream. These species have been identified by Mr. Banks as *Taeniopteryx nigripennis* and *T. pallida*. The former species was much the commonest, is smaller than *T. pacifica*, being only 9 mm. in length, and is black. *T. pallida* is slightly larger, and brown, with light wings. The foliage along the stream had quite a ragged appearance, as these species were very numerous and feeding voraciously. The plants affected, in the order of the preference of the stoneflies for them, were the thimbleberry (*Rubus parviflorus*), alder (*Alnus tenuifolia*), willows (*Salix* spp.), wild rose (*Rosa* sp.), serviceberry (*Amelanchier* sp.), and maple (*Acer douglasii*).

The mouth parts of these species have been examined and found to be very similar to those of *T. pacifica*. They are, of course, smaller, but fully as well equipped for biting soft plant tissues.

On April 25, 1917, a single stonefly was observed at Salem, Oreg., feeding on young cherry leaves. This specimen was captured, and has been determined as *Taeniopteryx* sp. by Mr. A. N. Caudell, of the Bureau of Entomology. A search failed to reveal any more specimens.

One may conclude from these observations that a study of the habits of stoneflies in other parts of the country, particularly those of the genus Taeniopteryx, will bring to light other plant-feeding and, hence, potentially injurious species.

PLATE 2

Taeniopteryx pacifica:

A.—Young peach leaves and blossoms injured by stonefly.
B, C.—Adult stoneflies feeding on peach buds.

A
B
C

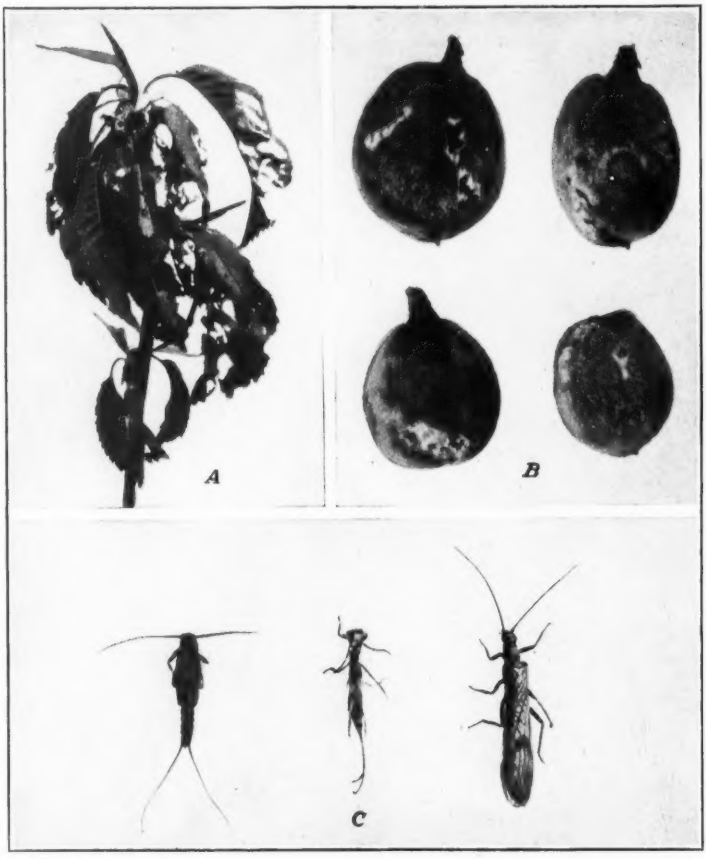

A
B
C

PLATE 3

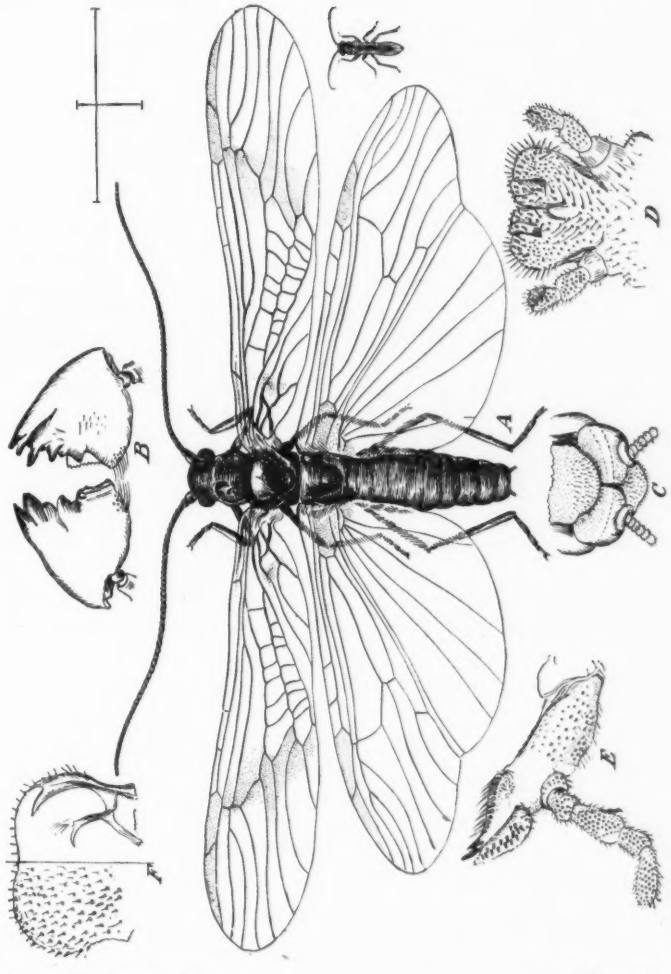
Taeniopteryx pacifica:

A.—Cherry foliage injured by stoneflies.
B.—Partly grown peaches, showing injuries caused by stoneflies.
C.—Nymph, cast nymphal skin, and adult stonefly.

PLATE 4

Taeniopteryx pacifica:

A.—Stonefly, much enlarged, and natural size.
B.—Mandibles, ventral view. Right mandible at reader's left.
C.—Ventral view of anal segment of female.
D.—Labium.
E.—Maxilla.
F.—Labrum. Dorsal view at left, ventral view at right.


A
B
C
D
E
F

BASAL KATABOLISM OF CATTLE AND OTHER SPECIES

By HENRY PRENTISS ARMSBY, *Director*, J. AUGUST FRIES, *Assistant Director*, and WINFRED WAITE BRAMAN, *Associate, Institute of Animal Nutrition of The Pennsylvania State College*

COOPERATIVE INVESTIGATIONS BETWEEN THE BUREAU OF ANIMAL INDUSTRY OF THE UNITED STATES DEPARTMENT OF AGRICULTURE AND THE INSTITUTE OF ANIMAL NUTRITION OF THE PENNSYLVANIA STATE COLLEGE

INTRODUCTION

The term "basal katabolism" has become generally accepted as a convenient designation for that portion of the katabolism due to the fundamental vital processes as distinguished, on the one hand, from that arising from external muscular activities and, on the other hand, from that caused by the ingestion of food. It is the katabolism of the animal in a state of complete muscular rest and with the processes of digestion and resorption suspended. It is the irreducible minimum of metabolic activity consistent with a particular condition of the body.

The basal katabolism in this strict sense is to some degree an ideal conception, although a close approach to the ideal may be observed in the postresorptive condition during short periods of complete muscular relaxation. Basal katabolism as thus defined is, from a slightly different point of view, an expression of the minimum food requirement of the organism. Any surplus above this minimum may either be utilized for muscular activity or give rise to a storage of matter and energy.

As regards the necessary food supply, however, a knowledge of the basal katabolism in the strict sense is of limited utility. A state of complete muscular inactivity can not be maintained for any considerable time, while even slight exertion augments the katabolism to a marked degree. In estimating the food requirements for the performance of a given amount of work by man or domestic animals, or for the storage of a specific quantity of protein and fat in the form of meat or milk, the base line is afforded, not by the katabolism during short periods of absolute rest but by the fasting katabolism of the individual under average conditions of living. Particularly is this true of the feeding of domestic animals for the production of human food. The dairy cow or the fattening steer must receive enough feed to supply its incidental daily activities as well as its minimum katabolism in a state of absolute rest before any is permanently available for manufacture into milk or meat. This amount, commonly spoken of as the maintenance requirement, is measured by the fasting katabolism under average conditions and may be called the 24-hour basal katabolism. Obviously, this is not as sharply defined a conception as is the basal katabolism in the narrower sense, but its practical importance is evident.

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METHODS OF EXPERIMENTATION

The determination of the fasting katabolism of animals such as Carnivora, man, or swine, having a comparatively simple apparatus, is largely a question of experimental technic. With ruminants the case is different. Their digestive apparatus is capacious and complicated, and contains at all times a relatively large amount of feed in process of digestion. It seems scarcely possible by any moderate period of fasting to reach a condition corresponding to the postresorptive state in man or Carnivora. The fasting katabolism may, however, be obtained indirectly by a comparison of the total metabolism on two different amounts of the same feed in the manner described in previous publications (*1, p. 33; 2, p. 282; 3, p. 53; 6, p. 460*).[1] For example, a steer receiving two different amounts of the same mixed ration gave the following results:

Item.	Dry matter eaten daily.	Daily heat production.
	Kgm.	*Calories.*
Period 2	9.146	16,511
Period 1	4.463	10,905
Difference	4.683	5,606
Heat increment per kilogram of dry matter		1,197

Evidently, out of the total metabolism of 10,905 Calories in period 1, $1{,}197 \times 4.463 = 5{,}342$ Calories may be regarded as the heat production caused by the 4.463 kgm. of dry matter eaten, while the remainder, 5,563 Calories, is the basal katabolism.

Strictly speaking, the foregoing method of computation assumes that the heat production caused by the feed is a linear function of its amount. This can not be regarded as having been proved, but no distinct indications to the contrary have appeared within the range of our experiments, while Wood and Yule (*21, p. 239*) compute that in Kellner's respiration experiments on fattening cattle the gains expressed in terms of energy are proportional to the metabolizable energy supplied in excess of maintenance, which, of course, is equivalent to saying that the heat production is also a linear function of the feed supply.

Our investigations on the metabolism of cattle afford data for a number of computations of the basal katabolism. Full statements regarding the methods employed, the animals used, the feed consumed, etc., have already been published (*4, 5, 6, 7*). The designations of the experiments, animals, and periods in the following pages correspond with those in the publications cited.

In view of the very striking effect of standing in increasing the metabolism of cattle the basal katabolism per 24 hours has been computed

[1] Reference is made by number (italic) to "Literature cited," pp. 55-57.

separately from the observed rate of heat production during the intervals of lying and standing, respectively, and also for 12 hours standing and 12 hours lying per day, assumed as representing average conditions (Table I).

TABLE I.—*Computed 24-hour basal katabolism of cattle per head*

Feeding stuffs.	Experiment No.	Animal No.	Periods compared.	Basal katabolism.			Average live weight.	Approximate age.
				Lying 24 hours.	Standing 12 hours.	Standing 24 hours.		
				Cal.	*Cal.*	*Cal.*	*Kgm.*	*Months.*
Timothy hay	174	I	D–A	6,136	6,927	7,717	406	36
Red clover hay	179	I	1–2	2,992	6,502	7,006	533	48
Do	186	I	2a–1a	7,509	8,298	9,087	579	60
Do	186	I	2b–3b	8,157	8,828	9,499	571	60
Timothy hay	190	A	4–3	2,963	4,197	5,341	275	11
Do	190	B	4–3	1,979	3,445	3,487	192	13
Do	200,	A	4–3	5,395	5,845	6,277	403	23
Do	200	B	4–3	4,143	4,819	5,521	303	25
Do	207	A	4–3	4,489	5,105	5,695	511	35
Do	207	B	4–3	5,226	5,395	5,935	380	37
Alfalfa hay	208	D	1–2	2,449	2,525	2,602	167	9
Do	208	E	4–6	2,274	2,867	3,462	211	9
Alfalfa hay and mixed grain.	208	E	1–3	2,945	3,742	4,537	204	9
Alfalfa hay	208	C	4–6	2,696	3,759	4,841	282	9
Alfalfa hay and mixed grain.	208	C	2–3	3,209	4,370	5,532	264	9
Alfalfa hay	209	F	4–6	3,591	4,134	4,679	307	21
Alfalfa hay and mixed grain.	209	F	1–3	4,015	4,913	5,810	292	21
Maize stover	210	D	1–3	3,647	4,746	5,828	331	21
Mixed hay	211	D	1–5	5,124	6,601	8,066	444	33
Mixed hay and hominy feed.	211	D	3–2	4,298	5,921	7,531	451	33
Mixed hay	211	G	1–5	4,525	5,818	7,098	377	28
Mixed hay and maize meal.	211	G	3–2	4,577	5,446	6,403	378	28
Alfalfa hay	212	H	1–5	3,650	4,760	5,551	343	20
Alfalfa meal	212	H	2–6	2,545	3,314	4,142	339	20
Alfalfa hay	216	J	5–7	3,853	5,127	6,342	390	21
Alfalfa hay and starch	216	J	1–4	4,560	5,348	6,157	372	21
Alfalfa hay and mixed grain.	217	J	2–1	4,882	5,563	6,243	513	33
Do	217	J	3–4	6,474	7,544	8,618	649	33

In experiment 217 steer J was fattened previous to periods 3 and 4 with the result of greatly increasing his basal katabolism both per head and per unit of surface (*6*). The result in these two periods, therefore, does not seem to be comparable with the others and has been omitted in the following comparisons. Steer C had also been full-fed from birth for the production of baby beef, but was by no means so fat as the more mature steer J and has been included in the discussion.

The results of Table I are shown graphically in figures 1, 2, and 3 in which the crosses represent the individual results, the straight lines the mean katabolism computed in proportion to the live weight, and the curves the mean katabolism computed in proportion to the body surface as recorded in Table III. Both the tabulated results and the graphs show rather wide variations, perhaps due in part to the fact that the computation is one by difference. As would be expected, the basal katabolism increased in general with the size of the animal but with very considerable fluctuations. According to Rubner's surface law, the basal katabolism within the same species is approximately proportional to the two-thirds power of the live weight. To test the extent to which this was true in these experiments, the coefficient of correlation [1] of the basal katabolism with the live weight and with the two-thirds power of the live weight has been computed, with the results shown in Table II.

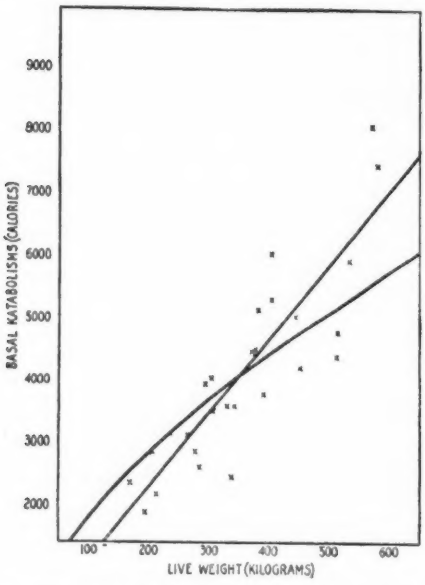

FIG. 1.—Graph of the basal katabolism of cattle per 24 hours' lying.

TABLE II.—*Coefficients of correlation*

	With live weight.	With two-thirds power of live weight.
Basal katabolism, lying 24 hours	0.8655±0.0326	0.9032±0.0239
Basal katabolism, standing 12 hours	.8733± .0308	.8710± .0313
Basal katabolism, standing 24 hours	.8548± .0350	.8250± .0415

Rather high coefficients were naturally to be expected, but the results fail to show any closer correlation with the two-thirds power of the weight than with the weight itself, a fact which is in harmony with Benedict's results upon man cited on a subsequent page.

[1] The statistical computations throughout this paper follow the methods described by C. B. Davenport in Chapter II of his "Statistical Methods with Special Reference to Biological Variation." (DAVENPORT, C. B. STATISTICAL METHODS, WITH SPECIAL REFERENCE TO BIOLOGICAL VARIATION. ed. 3, p. 19-18, fig. 4 New York, London, 1914.)

KATABOLISM PER UNIT OF SURFACE

Since, however, as appears from the foregoing comparisons, the body surface affords at least as satisfactory a reference unit as body weight, it seems desirable to follow the usual practice and compute the basal katabolism per unit of body surface. Such computations have generally been made by means of the formula proposed by Meeh (*15*)—viz, $S = k W^{\frac{2}{3}}$ in which S equals the body surface in square centimeters, W the body weight in grams and k a constant for the same species. Trowbridge, Moulton, and Haigh (*19*) have reported the weights and body surfaces of 35 beef steers and have computed the value of k for different classes of beef cattle. Moulton (*17*) has discussed the data further and has proposed for beef cattle the following modifications of Meeh's formula, which he regards as more accurate, in which W equals the empty weight in kilograms and S the body surface in square meters.

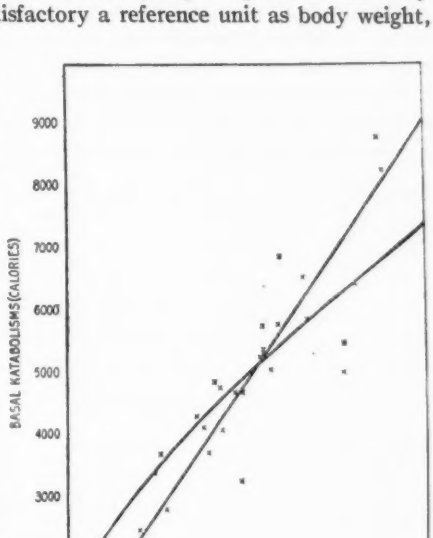

FIG. 2.—Graph of the basal katabolism of cattle per 12 hours' lying and 12 hours' standing.

For cattle in thin or medium condition ..... $S = 0.1186\, W^{\frac{2}{3}}$
For fat cattle ..... $S = 0.158$[1] $W^{\frac{2}{3}}$

Applying these formulas to the data of Table I, estimating the empty weight at 89 per cent of the live weight in the unfattened animals and 92 per cent in the full-fed steer C and in steer J, gives the results for the basal katabolism per square meter of surface shown in Table III. For steers C and J the formula for fat cattle has been employed.

The results upon steer J in experiment 217, periods 3 and 4, having been omitted as before, the frequency distribution of the remaining 27 results is shown in figures 4, 5, and 6. While the smoothed graphs show more or less divergence from the probability curve, especially for the results per 24 hours' standing, nevertheless, in view of the rather small number of observations, it would seem that the distribution may be regarded as fairly normal, at least in the two other cases. Assuming this,

[1] Erroneously printed as 0.134 in Moulton (*17*).

the ordinary statistical methods have been applied to the data of Table III, with the results recorded in Table IV. In considering the significance of these results it should be borne in mind that the experiments were upon 10 different animals and that in most instances those upon the same animal were made in different years. How far the factors of individuality and age thus introduced may affect the significance of the statistical calculations is a matter for future investigation. The results are recorded here for what they are worth.

TABLE III.—*Computed 24-hours basal katabolism of cattle per square meter of body surface*

Feeding stuffs.	Experiment No.	Animal No.	Periods compared.	Computed body surface.	Basal katabolism per square meter of body surface.		
					Lying 24 hours.	Standing 12 hours.	Standing 24 hours.
				Square meters.	*Cal.*	*Cal.*	*Cal.*
Timothy hay	174	I	D–A	4.706	1,304	1,472	1,640
Red clover hay	179	I	1–2	5.578	1,074	1,166	1,256
Do	186	I	2a–1a	5.875	1,278	1,412	1,547
Do	186	I	2b–3b	5.825	1,401	1,515	1,631
Timothy hay	190	A	4–3	3.693	802	1,136	1,446
Do	190	B	4–3	2.949	671	1,168	1,182
Do	200	A	4–3	4.690	1,150	1,246	1,338
Do	200	B	4–3	3.925	1,056	1,228	1,407
Do	207	A	4–3	5.437	826	939	1,047
Do	207	B	4–3	4.516	1,157	1,195	1,314
Alfalfa hay	208	D	1–2	2.707	905	933	961
Do	208	E	4–6	3.129	727	916	1,106
Alfalfa hay and mixed grain	208	E	1–3	3.067	960	1,221	1,479
Alfalfa hay	208	C	4–6	3.463	779	1,085	1,398
Alfalfa hay and mixed grain	208	C	2–3	3.340	961	1,308	1,656
Alfalfa hay	209	F	4–6	3.952	909	1,046	1,184
Alfalfa hay and mixed grain	209	F	1–3	3.832	1,048	1,282	1,516
Maize stover	210	D	1–3	4.147	879	1,144	1,405
Mixed hay	211	D	1–5	4.934	1,038	1,338	1,635
Mixed hay and hominy feed	211	D	3–2	5.028	855	1,178	1,498
Mixed hay	211	G	1–5	4.498	1,006	1,293	1,578
Mixed hay and maize meal	211	G	3–2	4.498	1,018	1,211	1,423
Alfalfa hay	212	H	1–5	4.236	862	1,124	1,310
Alfalfa meal	212	H	2–6	4.208	605	788	984
Alfalfa hay	216	J	5–7	4.589	840	1,117	1,382
Alfalfa hay and starch	216	J	1–4	4.458	1,023	1,200	1,381
Alfalfa hay and mixed grain	217	J	2–1	5.452	895	1,020	1,149
Do	217	J	3–4	5.506	1,176	1,370	1,565

TABLE IV.—*Basal katabolism of cattle per square meter of body surface*

	Lying 24 hours.	Standing 12 hours.	Standing 24 hours.
Mean.....Calories..	964	1,173	1,365
Probable error of mean.....do....	± 24.0	± 21.4	± 25.7
Probable error of single result.do....	±124.8	±110.9	±133.6
Standard deviation.....do....	185.1±17.0	164.5±15.1	198.0±18.2
Coefficient of variability.....	0.1920	0.1462	0.1451

The data of Table III also show a positive correlation between the basal katabolism per square meter of body surface and the live weight, especially for the lying position, as appears from Table V. In other words, the basal katabolism tended to increase more rapidly than the body surface.

TABLE V.—*Coefficients of correlation with live weight*

	Basal katabolism per square meter.
Lying 24 hours	0.5375±0.0923
Standing 12 hours	.3666± .1124
Standing 24 hours	.2405± .1223

MAINTENANCE REQUIREMENT OF CATTLE

In studying the results of feeding experiments it is often desirable to be able to estimate the maintenance requirements of animals. As already pointed out, this is not fixed by the basal katabolism in the narrower sense, but includes also the energy expended in a variety of incidental activities, more or less variable in amount, and corresponding to what we have here called the 24-hour basal katabolism. Our results demonstrate anew the marked influence of standing upon the metabolism of cattle, the mean 24-hour basal katabolism lying, standing 12 hours and standing 24 hours being in the proportion of 100:121:141, the difference largely exceeding the probable errors. For expressing the actual maintenance requirement we have customarily employed the results computed for 12 hours' standing, although this choice is purely arbitrary and any other ratio of standing to lying could be computed from the data of Table IV. If our previous practice be followed, the 24-hour basal katabolism—that is, the maintenance requirement—of an unfattened steer weighing 1,000 pounds (453.6 kgm.), equivalent to 403.7 kgm. empty weight, and standing half the time may be calculated by multiplying the basal katabolism per square

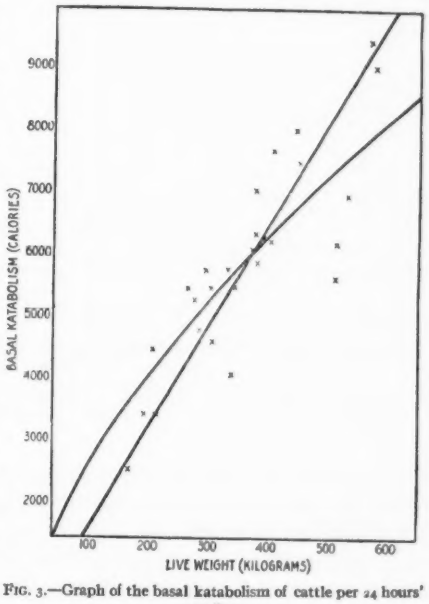

FIG. 3.—Graph of the basal katabolism of cattle per 24 hours' standing.

meter as recorded in Table IV by the body weight as computed by Moulton's formula (p. 47).

$$\text{Maintenance} = 1173 \pm 111 \times (0.1186 \times 403.7^{\frac{2}{3}}) = 5918 \pm 560 \text{ Calories.}$$

This result is substantially identical with that computed by the senior author (*2*, *p. 289*) from 23 of these same experiments in proportion to the two-thirds power of the live weight—viz, 5,906 Calories. No sufficient data seem to be available on which to base a similar computation for fattened animals.

RESULTS ON MAN

Numerous determinations of the basal katabolism of man have been reported, and it appears of some interest to compare their results with our data for cattle. We have not attempted to collate all the recorded experiments on man, but have taken as representative those reported by Benedict, Emmes, Roth, and Smith (*9*) and by Means (*14*), including 98 observation on men and 75 onwomen. These determinations were made in short periods in the post-resorptive condition and in a state of as complete muscular rest as practicable. The majority of them were determinations of the pulmonary respiration made with the Benedict respiration apparatus in periods of 10 to 20 minutes, although some were made with the bed calorimeter and extended over 2 to 3 hours. They therefore show substantially the basal katabolism in the narrower sense mentioned at the beginning of this article.

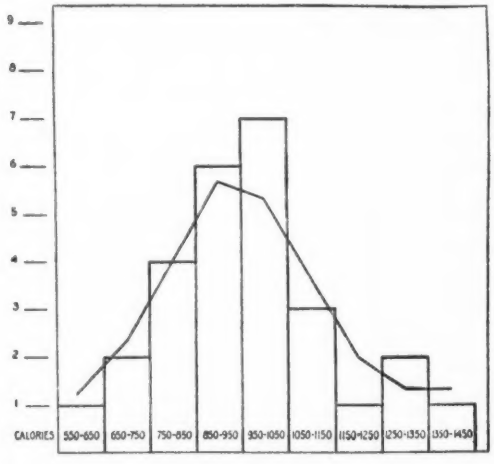

FIG. 4.—Graph of the frequency distribution of the basal katabolism of cattle per square meter of body surface lying 24 hours.

The graphs accompanying Benedict's discussion (*8*) of the results reported in the paper first cited present much the same picture as do our results on cattle as shown in figures 1, 2, and 3, failing to indicate any close relation of basal katabolism to weight or body surface. This conclusion is confirmed by a statistical study of the data, including those reported by Means, which yields the results of Table VI. The correlation coefficients are distinctly lower than those obtained with cattle, but, like them, they fail to show any greater correlation with the body surface as computed by the Meeh formula than with the body weight.

TABLE VI.—*Coefficients of correlation*

Total basal katabolism.	With body weight.	With body surface.
98 men	0.7263±0.0320	0.7747±0.0272
75 women	.7759± .0310	.7447± .0347

For further statistical study the results for the heat production per square meter of surface have been grouped in classes covering a range of 25 Calories in the case of men and 31 Calories in the case of women. The frequency distribution of these classes is shown in figures 7 and 8.

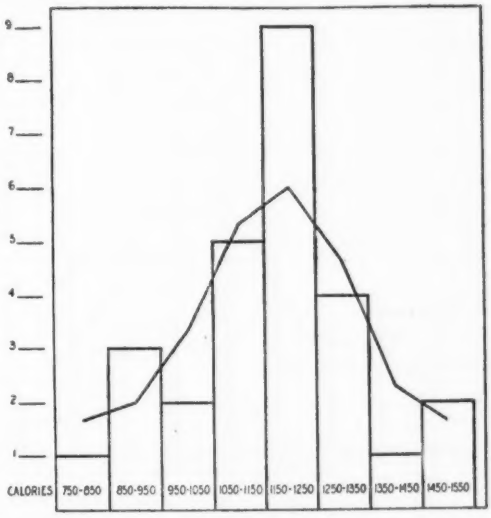

FIG. 5.—Graph of the frequency distribution of the basal katabolism of cattle per square meter of body surface lying 12 hours and standing 12 hours.

The data corresponding to those for cattle recorded in Table IV are contained in Table VII. As would have been expected from the more direct method available in experiments on man, the variability and the probable error are much lower than in the experiments on cattle.

TABLE VII.—*Daily basal katabolism of men and women per square meter of body surface*

	Men.	Women.
Mean ..... Calories	830	768
Probable error of mean ..... do	±4.3	±4.9
Probable error of single result ..... do	±42.3	±42.8
Standard deviation	62.7±3.0	63.5±3.1
Coefficient of variability	.0755	.0827

TABLE VIII.—*Corrected daily basal katabolism of men and women per square meter of body surface*

	Men.	Women.
Mean ..... Calories	935	886
Probable error of mean ..... do	± 4.8	± 5.8
Probable error of single result ..... do	±47.5	±49.4

In all these experiments the body surface was computed by the Meeh formula. D. and E. F. DuBois (*10*) have shown that the use of this formula gives too high results for the body surface of man as compared with direct measurement or with their "linear formula" and have also devised (*11*) a "height-weight chart" for the computation of body surface.

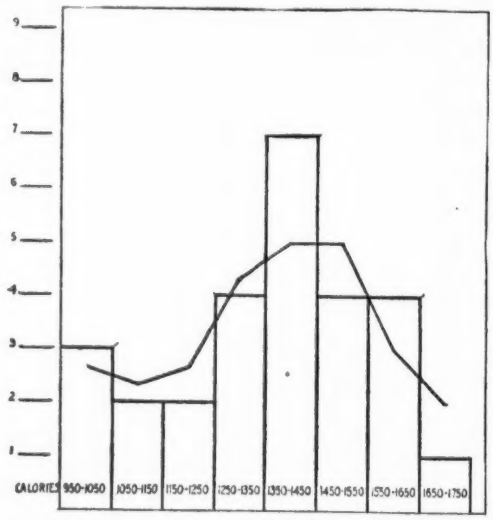

FIG. 6.—Graph of the frequency distribution of the basal katabolism of cattle per square meter of body surface standing 24 hours.

Recomputing Benedict's and Mean's results by this latter method, Gephart and E. F. DuBois (*13*) estimate the mean basal katabolism to be 38.97 Calories per square meter per hour for 88 men and 36.9 Calories per square meter per hour for 68 women. Correcting the figures of Table VII in this proportion the basal katabolism per 24 hours and the probable errors are as shown in Table VIII. Considering that these means represent a condition of minimum muscular activity they show a rather striking approximation to that for cattle in the lying position but otherwise free to move.

RESULTS ON THE HOG AND THE HORSE

Determinations of the basal katabolism of swine have been reported by Meissl, Strohmer, and Lorenz (*16*) and by Tangl (*18*), while Fingerling, Köhler, and Reinhardt (*12*) have computed it from a comparison of the gains made at two different ages and weights by growing pigs. Their results per square meter of body surface (estimated by Meeh's formula, using for k the value 9.02 found by Hecker for the horse) are recorded in Table IX. In both Tangl's and Fingerling's experiments the animals spent most of the time in the lying position. Meissl makes no statement on this point.

TABLE IX.—*Basal katabolism of swine per 24 hours per square meter of body surface*

Investigators.	State of animal.	Basal katabolism.
		Calories
Meissl et al	Mature animals	1, 117
		1, 084
Tangl	do	1, 063
		1, 066
Do	Growing animals	1, 139
		1, 068
Fingerling et al	do	1, 129
		960
Mean		1, 078

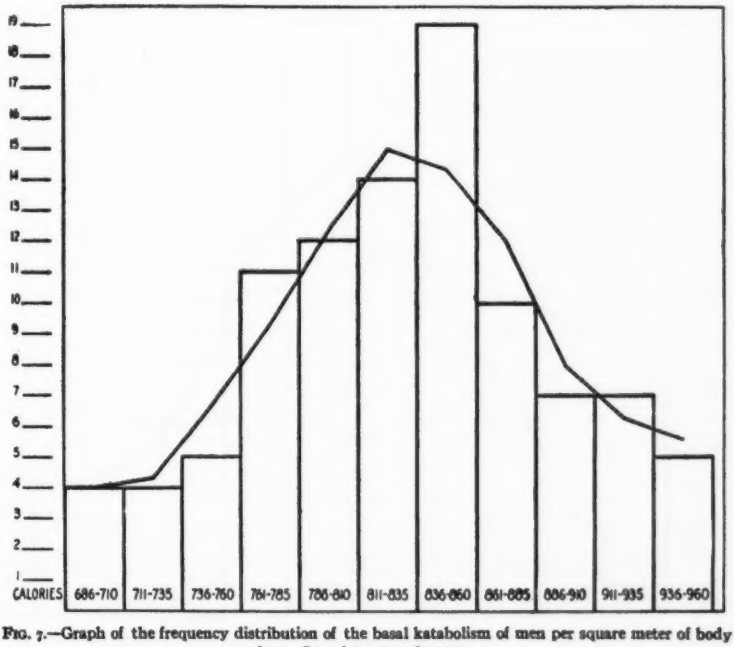

FIG. 7.—Graph of the frequency distribution of the basal katabolism of men per square meter of body surface. Complete muscular rest.

Zuntz and Hagemann (*22*, p. 284) have computed the basal katabolism of the horse from the results of numerous determinations of the respiratory exchange while standing quietly. Their method of computation is in principle the same as that which we have used for cattle, although the experimental methods are entirely different. Their results were as shown in Table X.

TABLE X.—*Computed fasting katabolism of the horse per square meter of body surface per 24 hours*

Period.	Season.	Calories.
a	Winter	807
b	Summer	767
e	Winter	879
f	Summer	936
i	Winter	802
n	Summer	1,085
c	do	976
No. 118c	Winter	1,333
Mean		948

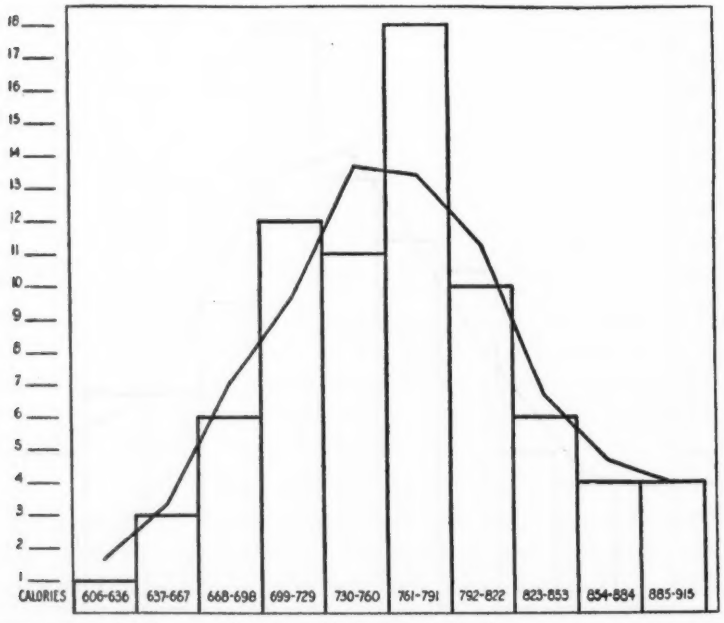

FIG. 8.—Graph of the frequency distribution of the basal katabolism of women per square meter of body surface. Complete muscular rest.

Zuntz and Hagemann regard the lowest of these values, obtained on an exclusive hay ration, as representing the basal katabolism of the horse and regard the higher results as due to a stimulation of the metabolism in periods of light feeding or of low temperature for the sake of heat production—i. e., to a "chemical" regulation of the body temperature.

COMPARISON OF SPECIES

Summarizing the foregoing means from the different species affords the comparisons of Table XI. Considering the nature of the results, they show a rather striking degree of uniformity and tend to confirm the conclusions of Voit (*20*) that the basal katabolism of different species of animals is substantially proportional to their body surface. It may be surmised that the exceptional result with the hog may be due to the imperfect data available for computing the body surface of this species.

TABLE XI.—*Mean daily basal katabolism per square meter of body surface*

Species.	Basal katabolism.
	Calories.
Men (complete muscular rest)	935±5
Women (complete muscular rest)	886±6
Cattle (lying)	964±24
Hogs (lying)	1,078±?
Horse (standing quietly)	948±?

SUMMARY

(1) The results of 27 determinations of the daily basal katabolism of unfattened cattle of different weights and ages are reported.

(2) The basal katabolism, whether computed lying or standing or for an equal proportion of each, was equally well correlated with the estimated body surface and with the live weight.

(3) The basal katabolism per unit of body surface showed considerable variability and a positive correlation with the live weight.

(4) The mean basal katabolism lying, standing 12 hours, and standing 24 hours was in the proportion of 100:121:141.

(5) The mean daily katabolism of a 1,000-pound, unfattened steer standing 12 hours out of the 24 is computed to be 5,918±60 Calories.

(6) Experiments upon man have given results regarding the correlation between basal katabolism and weight or body surface which substantially correspond with those upon cattle.

(7) The mean daily basal katabolism per square meter of body surface appears not to differ greatly in man, cattle, swine, and horses under comparable conditions.

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FURTHER NOTES ON LASPEYRESIA MOLESTA[1]

By W. B. WOOD, *Entomological Assistant*, and E. R. SELKREGG, *Scientific Assistant*, *Deciduous Fruit Insect Investigations, Bureau of Entomology, United States Department of Agriculture*

INTRODUCTION

Since the publication of a preliminary paper in the Journal of Agricultural Research,[1] investigations on the life history, habits, and control of the oriental peach moth (*Laspeyresia molesta* Busck) have been under way and additional information has been obtained on these points, as well as on its origin, distribution, and food plants.

The fears expressed in the publication cited, namely, that this insect might become a dangerous enemy of deciduous fruits, seem to have been well founded. Owing to the number of generations developing in a single season it is particularly hard to control, and this fact, together with its wide range of food plants, would seem to make it a pest of as great importance as its near relative, the codling moth, *Laspeyresia pomonella* Linnaeus, should it become generally distributed throughout the fruit-growing regions of the country. It is quite probable that it will eventually become widely distributed because of its fruit-feeding habits and its manner of hibernation if measures can not be taken to confine it to its present limits.

ORIGINAL HOME

There is now little doubt that this insect has come to us from Japan, probably in shipments of flowering cherries, or peaches and other fruits, received in the last six or eight years. Where infestations have been found in widely separated localities, shipments of flowering cherries from Japan have, in every instance, been traced to these points. Evidence of this character first led to the belief that the insect came from that country.

In correspondence with Mr. C. Harukawa, of the Ohara Agricultural Institute, Kurashiki, Okayama, Japan, it was learned that a similar insect was doing considerable injury to peaches and pears in that country.

[1] The work on which this paper is based was carried on by the writers under the direction of Dr. A. L. Quaintance, who supervised the operations throughout the season. For assistance in the preparation of the paper the writers express their thanks to Mr. Carl Heinrich, who drew up the description of the larva, furnished the information in regard to characters for separating *Laspeyresia molesta* from the larvæ of similar insects, and approved the drawings of the insect; to Miss Margaret Moles for her careful work in making the drawings; and to Mr. J. H. Paine for the photographs here used.

[2] QUAINTANCE, A. L., AND WOOD, W. B. LASPEYRESIA MOLESTA, AN IMPORTANT NEW INSECT ENEMY OF THE PEACH. *In* Jour. Agr. Res., v. 7, no. 8, p. 373-378, pl. 26-31. 1916.

Mr. Harukawa stated that the insect had been present there for about 10 years. He very kindly sent specimens of the Japanese insect for comparison and study, and Mr. August Busck, of the Bureau of Entomology, United States Department of Agriculture, determined it as *Laspeyresia molesta*. The evidence seems conclusive that this insect occurred in Japan before its introduction into the United States, but the location of its original home is a matter of conjecture.

FOOD PLANTS

At first it was thought that the only plants attacked were peach and the various cultivated species of Prunus, including cherry, plum, apricot, and several varieties of flowering cherries, but during the past season the insect was reared from quince, pear, apple, and flowering quince. It attacks the quince and apple almost as readily as it does the peach, and the injury caused would undoubtedly be very severe in a large plantation. Of the pome fruits, the quince is the favorite food plant, to judge from the number of insects reared from the fruit. From 10 quinces 93 insects were reared, making an average of more than 9 to each fruit. The late apples also were badly infested. Very little injury was noticed on the twigs of apples, but almost every twig on the quince trees was hollowed at the tip.

DISTRIBUTION IN THE UNITED STATES

From records at hand the insect is present only in the Eastern States. In addition to the locality approximately given as the District of Columbia and adjacent territory it is recorded from northern New Jersey, New York City, Long Island, and Stamford, Conn. Doubtful records come from points near Albany and Buffalo, N. Y., and from southwestern Pennsylvania, but these have not yet been verified. In all localities where the insect has yet been found, with the exception of the vicinity of Washington, D. C., the fruit-growing industry is unimportant and in some places, as in New York City, the only apparent food plants were flowering cherry and flowering quince. If the infestation should extend to regions where fruit is extensively grown and shipped to other parts of the country, the distribution of the insect would almost certainly take place by transportation of the larvæ, either in the fruit or in cocoons on the outside. There is danger also of disseminating the insect by shipping nursery stock bearing hibernating larvæ. Without doubt it was in this way that it first entered the country and reached the localities where it is at present found. It may also spread for short distances from orchard to orchard by flight, as the moth is a strong flier at dusk and in the late afternoon on cloudy days.

CHARACTER AND AMOUNT OF INJURY

The character of injury and amount of damage vary at different seasons of the year, and on different food plants. The damage resulting

from each of the early generations is separated from that occasioned by the next generation by an interval during which no freshly injured twigs can be found. This interval comes in the period between the attainment of full development by the larvæ of one brood and the appearance of the newly hatched larvæ of the next. The interval between the first and second generations and that between the second and third are quite noticeable to one who is making observations in the orchard, but after the third generation the broods of larvæ overlap to such an extent that they can not be thus defined. The injury resulting from each successive generation increases in severity as the season advances, until late summer. In 1917 the number of moths produced by the overwintering larvæ appeared to be small and the amount of injury from the first brood of larvæ was proportionately so, only a few injured twigs showing here and there through the peach orchard. The second-brood injury was much more noticeable and the injury from the third was quite severe. The fourth caused less damage to the twigs than the third, while the fifth brood, appearing late in October, caused almost no injury. In the latter part of the season the insects diminished in numbers on trees without fruit and the overwintering larvæ were few, in comparison to the large number of larvæ of the third generation and the early part of the fourth. It was only on the trees bearing late-ripening varieties of peaches or in the pome fruits that the larvæ of the fourth generation appeared to develop in large numbers.

The injury caused by this insect is of two distinct kinds—namely, injury to the twigs and injury to the fruit. The former is particularly severe on young trees, and occurs mostly before midsummer, while the twigs are yet soft; the latter form does not become severe until after August 1.

TWIG INJURY

The injury to the twigs is first noticed in the spring when the young shoots are about 6 inches long. It is caused by the boring of the larvæ which enter near the tip of the twigs or in the petiole or midrib of the leaves. The injury caused by the newly hatched larvæ may not be noticed for several days after the insect has begun work if the weather is cool and damp, but it appears much sooner if the weather is hot. On peach it usually shows plainest at midday or in the afternoon and is characterized at first by a slight wilting of a single leaf or in some cases the whole tip of the twig and by a very small amount of frass thrown out of the tunnel at the point of entrance. As the insect feeds it increases in size and the tunnel is enlarged accordingly. As the tunneling proceeds the tip of the twig continues to wilt and finally dies. Usually before the twig has completely dried the insect leaves it to find another feeding place or to spin a cocoon if it has fully developed. A larva seldom reaches full development in a single twig unless it be of the thick

type found in some cherries. In slender shoots, such as peach, three, four, or five tips usually will be killed before the larva has matured (Pl. 5, A) Another type of twig injury is found on peach in late summer and fall after the twigs have hardened and stopped growing and after the fruit is gone. This is found usually at the site of previous attack where the gum has exuded and adhered to the bark, sticking fast dead leaves and other débris (Pl. 5, B). In this mass the larva starts work, causing more sap to exude and the twig to swell and in some cases to develop a gall-like formation. The larva mines in the bark and wood of such a twig usually until ready to spin a cocoon. The first six or eight buds below the terminal also may be injured by the late-working larvæ.

The amount of twig injury varies considerably on different food plants, the peach coming first in severity of attack. Young cherries of a number of varieties and the varieties of flowering cherry are very severely injured. Quince probably comes next in the list of injured plants, with plum, apple, pear, nectarine, and apricot following.

FRUIT INJURY

Injury is first noticed in peaches about the time the fruit is the size of chestnuts or slightly larger. In other fruits it has not been noticed so soon. The early injury is caused by larvæ of the second generation, the first-brood larvæ confining themselves almost entirely to the twigs while the fruit is yet small. The second-brood larvæ begin working in the twigs, but when about half grown a few of them turn their attention to the fruit. They bore into the side of the peach (Pl. 6, A, B) and tunnel through the fruit until they are fully developed, emerging sometimes at the point of entrance but most generally through another hole. Such injury usually does not cause the peach to rot or fall to the ground while the fruit is green and hard, but the sap exudes from the wound in the peach, forming a smear of gum on the outside. Frequently the larva, after making a hole in a peach, is apparently "drowned out" by the sap. The sap continues to flow, causing the same gummy appearance of the peach as though the insect had continued to work in the fruit. Most of the third-brood larvæ begin work in the twigs in the same way as the previous broods. A few, however, attack the peach as soon as they are hatched. At this time the early midseason varieties of peaches are ripening and the insect finds it easier to gain entrance to the fruit than when it is green. In a few days nearly all of the insects of this brood desert the twigs for the fruit, and it is at this time that the severe injury to the fruit begins. Varieties of peaches ripening after the 1st of August are all subject to severe injury.

The spot on the fruit most often selected as a point of entry is the area surrounding the stem. When the fruit is beginning to soften the larvæ work beneath the skin at this point and go directly to the seed, leaving in many cases no sign that they have entered. Sometimes,

however, a small amount of frass is left at the point of entrance. The small larvæ may not be discovered even after opening the fruit, for at first they work along the grooves in the seeds. Another favorite point of entrance is between two peaches which hang against each other or on the surface of a peach on which a leaf is resting (Pl. 6, A). This seems to give the larvæ a better foothold than they can find on the open surface of the fruit.

The fourth-brood larvæ begin to hatch in time to attack late-ripening Elberta and varieties that ripen still later, Smock being badly damaged. The attack continues until late in the fall after all peaches have been picked.

Larvæ of the fifth generation that hatch early may appear in time to attack the latest-ripening varieties of peaches, but their work is confined mostly to the peach twigs, where they cause little injury, and to the pome fruits, such as quince and apple.

Injury was not noticed on the pome fruits until late in August, and it is thought that before this time they are not heavily attacked. Later, however, the infestation appeared to be serious. From 1½ bushels of medium-sized Ben Davis apples showing signs of injury (Pl. 7, A, B) 354 larvæ of *Laspeyresia molesta* were reared. Fifty per cent or more of the fruit in the orchard from which these apples were taken were injured. In another apple orchard about a half mile distant from the infested peach orchard very little injury was found. Quince was more severely injured than apple (Pl. 6, B). In a row of several trees not a sound fruit could be found, and, as mentioned before, the average number of insects reared from each of 10 quinces, picked at random, was more than 9 per fruit. Even though commercially the injury to pome fruits might not be severe, such food plants are of great importance in that they affect materially the problem of control by furnishing food for the insect in the fall after other fruits have disappeared. The mortality among newly hatched larvæ is probably very great in peach orchards after the twigs have hardened and the fruit is gone, but quinces, apples, or pears furnish an ideal place for the development of the late broods. Such fruits in the vicinity of a peach orchard doubtless form a reservoir from which the infestation spreads the following spring. Cherry and plum ripen too early in the season to be severely injured by this insect. On several cherry and plum trees growing beside an infested peach orchard not one injured fruit was found.

As previously stated, the periods of attack by the first, second, and third generations do not overlap, and there is a period between each generation when no insects can be found working in the twigs or fruit. The larvæ of the third and of the following generations appear over a much longer period of time and before the latest individuals of one generation have developed the larvæ of the following generation are at work. Because of this overlapping of the later broods it was not pos-

sible to tell when one generation had developed fully or when another had begun work, except by rearing the insects through the season under conditions as nearly natural as possible.

Table I shows the dates of the beginning of severe injury to peaches by each brood of larvæ, the percentages of fruit injured as shown by counts in definite periods throughout the summer, and a few varieties of peaches ripening in each period.

TABLE I.—*Dates of injury to peaches by respective broods of larvæ of the oriental peach moth, Arlington Farm, Va., 1917*

Date of beginning of severe injury.	Percentage of peaches injured in period from—	Common varieties of peaches ripening in periods named in column 2.
By first generation, May 31.	May 31 to June 30....0.	Greensboro.
By second generation, July 6.	July 1 to July 15...2.5.	Greensboro. Waddell.
	July 16 to July 31....3.	Carman. Hiley.
By third generation, July 28.	Aug. 1 to Aug. 15...18.	Champion. Early Crawford. Bell. Old Mixon Free. Reeves.
	Aug. 16 to Aug. 31..28.2.	Elberta. Late Crawford. Chairs.
By fourth generation, Aug. 30.	Sept. 1 to Sept. 16...53.	Smock. Stump.
By fifth generation, Oct. 7.	Sept. 17 to Oct. 20, no count made. All fruit harvested.....	Salway. Bilyeu.

INSECTS LIKELY TO BE CONFUSED WITH THE ORIENTAL PEACH MOTH

There are several insects which may be confused with *Laspeyresia molesta* in the larva stage, either because of a close resemblance or because of a similarity in the injuries which they cause. The more common of these are the codling moth, *Laspeyresia pomonella* Linnaeus; the lesser apple worm, *L. prunivora* Walsh; the peach twig borer, *Anarsia lineatella* Zeller; and *Laspeyresia pyricolana* Murtfeldt.

L. pomonella is likely to be mistaken for *L. molesta* in the fruit of the apple, pear, and quince, but close examination will show several points of difference in the mature larvæ. The following characters serve to separate the larvæ of the two species: On *L. pomonella* (Pl. 8, G) the anal fork is absent; a scobinated pad is present extending across the anal proleg just in front of the crochets; the crochets on abdominal prolegs are 23 to 38 in number. On *L. molesta* (Pl. 8, F) the anal fork is present, situated just below the anal plate and above and behind the anal prolegs; the scobinated pad is absent; the crochets are 31 to 46 in number. The full-grown larva of *L. molesta* is smaller than that of *L. pomonella*.

L. prunivora works in apple, causing injury to fruit almost identical with that caused by *L. molesta* (Pl. 7, A); it does not injure twigs. Specimens of larvæ were not available for comparison. Superficially they appear the same as *L. molesta*.

Anarsia lineatella attacks peach twigs, causing injury identical with the spring injury of *L. molesta* (Pl. 5, A). The larva is most readily separated from *L. molesta* by the setal plan of the ninth abdominal segment, which should be compared with that shown in Plate 8, D. In *Anarsia lineatella* seta I is not approximate to seta III, being farther from or at least as far from seta III as from seta II; the frons extends almost to the incision of the dorsal hind margin; the longitudinal ridge is extremely short; setæ P_1 and P_2 and puncture P_b lie in a line; P_2 is well behind the level of Adf_2.

Laspeyresia pyricolana attacks the twigs of apple, boring out the center and killing the tip. The injury resembles that of *L. molesta* on apple twigs. No specimens were available for comparison.

LIFE HISTORY AND HABITS

The following data on the life history of *Laspeyresia molesta* are based on material collected chiefly at the United States Department of Agriculture experimental farm near Rosslyn, Va., and reared in the insectary at the Bureau of Entomology, Washington, D. C., during the season of 1917. The insectary provides practically outdoor conditions where insects may develop normally.

SPRING EMERGENCE AND OVIPOSITION

In mid-March hibernating larvæ pupate and about mid-April, or when peaches are in full bloom, the first adults emerge, their emergence continuing through the first three weeks of May. The time elapsing between emergence and the beginning of oviposition, called the preoviposition period, ranges from 2 to 12 days and averages 5 days. In 1917 the first eggs were found in a peach orchard on May 3. Normally the eggs are deposited singly on the under side of the leaves, and in the orchard they were not found in any other place. In glass rearing jars an occasional egg was deposited on the upper surface of the leaf, and in one case four eggs were found on the bark of a peach seedling confined in a rearing cage. The moths oviposit much more freely on the smooth glass surface of the battery jar and lantern globe rearing cages than on peach foliage placed in the jar; hence eggs used for study were those deposited on the glass of the rearing cages.

The deposition of eggs began May 2 and continued until late in the fall. The last egg observed was found October 8. At this time development had proceeded far enough to show the eye-spots in the embryo.

THE EGG

The egg (Pl. 9, B), is scalelike, oval, slightly convex, flattened toward the edge; color grayish white, somewhat iridescent; average measurement 0.59 by 0.72 mm. Central surface finely granulate with reticulating ridges extending from the edge toward, but not to, the center.

The average incubation periods in 1917 for eggs of the first three generations, respectively, were 7.5, 4, and 3.1 days. For eggs of the fourth and fifth generations, collectively, the incubation period was 8.3 days.

The progress of development in the egg can be readily observed through its thin shell. In midsummer the progress is so rapid that the embryonic outline is easily discernible 12 hours after deposition. The darkening of the head is first evidenced by the appearance of eyespots. A large majority of the eggs hatch in the late afternoon, during periods when the temperature is high enough to insure steady development. When ready to be hatched the young larva makes rather vigorous movements of its head and mandibles against the eggshell, which finally is slit open and the larva walks out. In one instance when the hatching of an egg was closely observed, 57.5 minutes elapsed from the time of the first movement of the mandibles of the larva until it had entirely quitted the eggshell.

THE LARVA

The larva (Pl. 9, A) is cylindrical; without secondary hair; color varying from white to deep pink, usually more strongly suffused with pink on dorsal side. Legs and prolegs normal. Crochets (31 to 46) uniordinal, in a complete circle. Anal fork developed, yellow to black in color, three to six pointed, prominent. Setal areas broadly chitinized, grayish brown. Thoracic shield light yellow edged with yellowish brown, narrowly divided, moderately broad. Spiracles dark brown or black, small, circular, slightly produced; spiracle on prothorax and that on abdominal segment 8 very little larger than those on abdominal segments 1 to 7. Entire body, except chitinized areas, evenly and finely scobinate; what appears to be a coarse pubescence under low magnification proves, under high magnification, to be a mass of short aculei.

Body setæ (Pl. 8, D) yellow shading to deep brown, moderately long. Prothorax with Ia and Ib on, and Ic behind the anterior margin of the shield; IIa and puncture y caudad of Ia; IIb directly laterad of IIa; puncture x dorsad of and approximate to Ib, lower than the level of IIb; Ib, Ic, and IIc equidistant; prespiracular shield oval, situated ventro-cephalad of the spiracle, bearing three setæ; group VI bisetose. Mesothorax and metathorax with VI unisetose. Abdominal segments 1 to 7 with II longer than and ventro-caudad of I; III over the spiracle; IIIa approximate to III, dorso-cephalad of the spiracle; IV and V on the same chitinization, under the spiracle, approximate. Abdominal segment 8 with II only slightly below the level of I; III and IIIa cephalad of the spiracle. Abdominal segment 9 with all setæ in a line, I and III closely approximate; V, IV, and VI on the same chitinization, approximate; VII unisetose.

Head light brown, with darker brown mottling; hind margin, ocellar area, and tips of trophi black.

Head capsule (Pl. 8, A, B, C) nearly spherical, slightly flattened, broadly oval in outline viewed from above, a little wider than long; greatest width well behind the

middle; incision of dorsal hind margin about one-fourth the width of the head; distance between dorsal extremities of hind margin less than one-half the width of the head. Frons (Fr) only slightly longer than wide, reaching to middle of head; adfrontal ridges (AdfR) sinuate; longitudinal ridge half the length of the frons; adfrontal suture (AdfS) reaching to dorsal incision of hind margin. Projection of dorsal margin over ventral slightly less than one-third the diameter of the head.

Ocelli six, in the normal tortricid arrangement; III, IV, and V in a straight line; I larger than the others.

Epistoma with the normal setæ (E_1, E_2).

Frontal punctures (F^a) lying rather closely together, anterior to the setæ (F_1); distance between punctures less than from puncture (F^a) to seta (F_1); adfrontal seta (Adf_1) nearer to F_1 than to Adf_2; adfrontal puncture (Adf^a) approximate to Adf_2.

Epicranium with the normal number of primary setæ and six punctures, and with three small ultraposterior setæ and one ultraposterior puncture. Anterior and lateral setæ (A_1, A_2, A_3, and L_1) in a line, with distances between A_1 and A_2, A_2 and A_3, and A_3 and L_1 about equal; puncture (A^a) postero-dorsad of A_2; A_1, A_2, and A_3 on a level respectively with F^a, F_1 and Adf_1. Posterior setæ (P_1 and P_2) and punctures (P^a and P^b) at middle of head; P_1 on a level with adfrontal puncture (Adf^a); P_2 and puncture (P^b) on a level with beginning of longitudinal ridge (LR); P_2, P_1, and adfrontal seta (Adf_1) in a line; puncture (P^a) approximate to and equidistant from A_3 and L_1. Lateral seta (L_1) on a line with P_1 and adfrontal puncture (Adf^a); lateral puncture (L^a) directly posterior to the seta. Ocellar setæ (O_1, O_2, O_3) well separated. O_1 closely approximate to and equidistant from ocelli II and III, within the area bounded by the ocelli; O_2 closely approximate to and postero-ventrad of ocellus I; O_3 postero-ventrad of and remote from O_2, slightly below the level of ocellus VI; puncture O^a absent. Subocellar setæ (So_1, So_2, So_3) triangularly placed. So_2 and So_3 closer together than So_2 and So_1; puncture (So^a) lying midway between So_2 and So_3. Genal seta (G_1) and puncture (G^a) both present; puncture anterior to the seta.

Length of full-grown larva 11 to 13 mm.

When the young larva hatches it immediately starts on its search for a favorable feeding place. In one instance 20 minutes were required after hatching for a larva to explore three peach leaves and to make its way to the tender growth at the terminal, where it bored into the interior of the peach shoot. The larvæ do not feed as they enter, but withdraw their heads from the burrow and cast aside the fragments of tissue until the more succulent interior of the twig is reached. If the young larvæ fail to locate favorable feeding places in a short time they undoubtedly die, for in the rearing jars they die within 12 hours after hatching.

The length of time required for larvæ to develop fully varies considerably, the feeding period being from 8 to 16 days in length throughout the entire season and the average for 59 larvæ being 11.2 days. When the larva has fully developed it leaves the twig or fruit where it has been working and starts in search of a favorable place for spinning its cocoon. The spring and midsummer cocoons are formed mostly in the axils between twigs or on the fruit at the point where it is attached to the stem. The latter place is the one most often chosen. Occasionally a larva will spin on the open surface of the peach, but usually it selects a more sheltered spot. The cocoon is made of fine silken strands, the

exterior mixed with fragments of frass or of bark, or if it is on the surface of the peach the fuzz or pubescence from the skin of the peach will be incorporated in the cocoon. Occasionally in a dry fruit, such as quince, the insect will spin its cocoon inside of the fruit. The time from the spinning of the cocoon to pupation is from 2 to 9 days and the average 3 days.

THE PUPA

The pupa (Pl. 9, C, D, E) is yellow-brown in color; without pubescence; average measurements (3 specimens) 6.26 mm. long by 1.8 mm. wide. Frontoclypeal suture indistinct; eyes and glazed eyes discernible; mandibles and clypeus distinctly indicated; 2 pairs of clypeal setæ, inner pair slightly longer than outer; clypeo-labral suture not visible; labial palpi slightly more than half the length of the maxillæ; maxillary palpi extending to the proximo-lateral angles of the maxillæ; maxillæ reaching one-third of the way to the tips of the wings. Metathoracic legs and tips of hind wings reaching just beyond the cephalic edge of the fourth abdominal segment; antennæ extending about two-thirds of the wing length, reaching beyond second coxæ. A double row of dorsal spines on abdominal segments 2 to 7; abdominal segment 2 with spines of cephalic row uneven in size and arrangement, the row extending usually less than half-way across the segment, the caudal row well developed and extending almost across; segments 3 to 7 with spines of cephalic row about twice as large and half as numerous as those of the caudal row; segments 8 to 10 with one row of spines, the spines gradually increasing in size from segment 8 to segment 10.

No cremaster. Two hooked setæ on either side of the anal rise, with a third hooked seta latero-caudad; a fourth pair of hooked setæ, dorso-caudad of the third pair, is on the caudal margin of the abdomen. Spiracles circular and produced. Anal and genital openings slitlike, the latter single in both sexes.

The pupa period covers from 5 to 12 days, averaging 7.8 days. When the moth is ready to emerge the pupa pushes itself from its cocoon by means of rows of dorsal spines on the abdomen. When it protrudes from the cocoon far enough to permit emergence of the moth the pupa fastens itself to the inside of the cocoon by means of hooked spines arranged upon the caudal margin. The pupal case then splits in the cephalic and thoracic regions, permitting the moth to emerge.

THE ADULT

The head of the adult[1] (Pl. 10, A, B, C) is a dark, smoky fuscous; face a shade darker, nearly black; labial palpi a shade lighter fuscous; antennæ simple, rather stout, half as long as the forewings, dark fuscous with thin, indistinct, whitish annulations. Thorax blackish fuscous; patagia fainly irrorated with white, each scale being slightly white-tipped. Forewings normal in form; termen with slight sinuation below apex; dark fuscous, obscurely irrorated by white-tipped scales; costal edge blackish, strigulated with obscure, geminate, white dashes, four very faint pairs on basal half and three more distinct on outer half besides two single white dashes before apex; from the black costal intervals run very obscure, wavy, dark lines across the wing, all with a strong outwardly directed wave on the middle of the wing; on the middle of the dorsal edge the spaces between three of these lines are more strongly irrorated with white than is the rest of the wing, so as to constitute two faint and poorly defined,

[1] Description by Mr. August Busck. (QUAINTANCE, A. L., and WOOD, W. B. LASPEYRESIA MOLESTA, AN IMPORTANT NEW INSECT ENEMY OF THE PEACH. *In* Jour. Agr. Research, v. 7, no. 8, p. 373-374. 1916.)

white dorsal streaks. All these markings are only discernible in perfect specimens and under a lens; ocellus strongly irrorated with white, edged by two broad, perpendicular, faint bluish metallic lines and containing several small deep black, irregular dashes, of which the fourth from tornus is the longest and placed farther outward, so as to break the outer metallic edge of ocellus; the line of black dashes as well as the adjoining bluish metallic lines are continued faintly above the ocellus in a curve to the last geminate costal spots; there is an indistinct, black apical spot and two or three small black dots below it; a thin but distinct, deep black, terminal line before the cilia; cilia dark bronzy fuscous. Hind wings dark brown with costal edge broadly white; cilia whitish; underside of wings lighter fuscous with strong iridescent sheen; abdomen dark fuscous with silvery white underside; legs dark fuscous with inner sides silvery; tarsi blackish with narrow, yellowish white annulations.

Alar expanse: 10 to 15 mm.

United States National Museum type 20664.

Adults emerged in 1917 from April 16 until October 30, though only a few straggling individuals emerged after October 5.

The preoviposition period for the entire season varied from 2 to 12 days, averaging 4.7 days, and there is some evidence that oviposition occurred in a few instances the day following emergence.

In the rearing cages the moths are quiet during the day, but become active during late afternoon and early dusk. Oviposition began in a few cases between 3 and 4 o'clock in the afternoon, and it usually continues throughout the dusk of evening.

In order to obtain eggs it was necessary to confine more than one pair of moths in each rearing cage. In one instance eggs were obtained in a jar containing one female and three male moths, but most satisfactory results were obtained by confining about 20 moths with a representation of both sexes in each jar.

In no case were eggs produced by isolated pairs. The recorded number of eggs deposited in rearing jars varied from 1 to 391. The single egg was produced in a jar containing 3 female moths and 1 male. A jar containing 12 female and 8 male moths produced the 391 eggs.

Adults are seen infrequently in the orchard during the day, but from late afternoon to late dusk they fly about the upper parts of the peach trees and in sheltered places between the trees. They are most active during early dusk. In the first part of August they appeared in such numbers that they were easily noticed, and by early September they were observed flying in large numbers. Their flight is rapid, erratic, and irregular, though occasionally they dart away in a definite direction. Moths thus seen actively flying were nearly all males. Of eight captured on the evening of August 20, four were females. One stroke of a collecting net captured them from a twig where two moths were seen to alight. Only one other female moth was captured in the field, though a large number of males were taken during August and September. The females in rearing cages fly as vigorously as the males, and there is little doubt that distribution of the insect throughout orchards and from one orchard to another takes place rapidly by means of flight.

HIBERNATION

The insect hibernates in the larva stage in cocoons spun in the autumn after the larvæ have fully developed. In the peach orchard a large percentage of the overwintering insects spin their cocoons in small cracks in the bark, under bark flakes, and in curled ends of bark strips on the trunk and large branches of the trees. The range of places for spinning is shown in the following list of locations in which cocoons were observed in April, 1917, at the United States Department of Agriculture experimental farm near Rosslyn, Va.: (1) Under edges of bark scales; (2) in axils of fruit spurs; (3) in the curled ends of scales of bark; (4) beneath scales at axils of secondary branches; (5) between mummied peaches on the trees and on the ground; (6) between peaches and the spur bearing them; (7) in old bark wounds; (8) in the frass at enlarged ends of twigs fed upon last season by the larvæ; (9) in the wrinkles of mummied peaches on the ground; (10) on the smooth bark of the twigs; (11) in burrows made by barkbeetles; (12) in holes formerly filled with pith at end of stub made by pruning; (13) in the hollows of stubble.

PARASITES[1]

Eight species of hymenopterous parasites have been reared. Six of them are primary and two are secondary parasites. One dipterous parasite, *Hypostena variabilis* Coquillett, was reared from larvæ collected in the orchard. It pupated within the partially constructed cocoon of the host. The host was probably attacked while the larva was seeking a cocooning place.

Of the six primary hymenopterous parasites, *Macrocentrus* sp. was most abundant. *Macrocentrus* sp. (Q. 7897) attacks and develops within feeding larvæ of *Laspeyresia molesta*, spinning its cocoon within the cocoon of the host. The latter may be thin and unfinished, due to the weakened condition of the larva. This species is also a parasite of the codling moth, *L. pomonella*. *Phaeogenes* sp. (Q. 7204) was second in abundance. Phaeogenes emerges from the pupa of the host and probably attacks the insects in the prepupa or pupa stage. Several specimens of *Ascogaster carpocapsae* Viereck were reared. According to Mr. Cushman, *A. carpocapsae* oviposits in the egg of the host, kills the insect as a larva after it has spun its cocoon, and spins its own cocoon within that of the host. One specimen each of *Spilocryptus* sp. (Q. 6833), *Mesostenus* sp. (Q. 1345), and *Glypta vulgaris* Cresson were reared. Spilocryptus attacks the host after the larva has spun its cocoon, and the adult parasite emerges from the pupa of the host. Glypta and Mesostenus attack the feeding larva and kill the host in the prepupa stage. Each one spins its cocoon within the cocoon of the host.

[1] Through the assistance of Mr. R. A. Cushman, of the Bureau of Entomology, United States Department of Agriculture, the writers are enabled to give the breeding habits of the parasites and the relation of the parasites to the host.

Of the two secondary parasites, *Dibrachys boucheanus* (Ratzeburg) pupated within and was reared from cocoons of *Macrocentrus* sp., already mentioned as a parasite of *L. molesta*. Of three specimens of *Cerambycobius* sp. (Q. 5195), two were found in cocoons of *Macrocentrus* sp.

OTHER NATURAL ENEMIES

A small spider was observed to kill a partly grown larva of *L. molesta*. The larva was evidently migrating from one feeding place to another when captured. On two occasions larvæ of lacewing flies were seen with the larvæ of *L. molesta* in their mandibles. In a few instances cocoons were found torn open and contents removed, evidently by woodpeckers.

CONTROL MEASURES

Because of its habit of feeding inside of the twigs and fruit, no success was obtained in controlling the insect on peaches by the use of poisoned sprays. Arsenate of lead, though applied to the fruit, foliage, and twigs just before the eggs were due to hatch, did not prevent the larvæ from entering the twigs and fruit and gave no degree of control. Other applications in addition to this one, made at such times as it was thought the insect would be most vulnerable to attack, gave no better results in control. A 40 per cent nicotine sulphate solution, diluted to 1 part in 400 parts of water and applied in the same way and at the same time as the treatments with arsenate of lead, did not control the insect; although counts made early in the season of the number of infested twigs on the sprayed and unsprayed plats seemed to indicate slight benefit from the treatment. A combination spray of lead arsenate and nicotine sulphate likewise gave negative results.

Banding the trees with burlap resulted in the capture of a few larvæ, but most of the insects, after leaving the twigs and fruit, spin their cocoons around the fruit spurs, on the peaches, and in the axils of the twigs, thus making this operation a failure.

Clipping the infested twigs from the trees and destroying them, and destroying infested fruit, gave partial control, but was too laborious to be practical.

Tests were made of the killing power of miscible oils and nicotine sulphate when applied to the cocoons containing overwintering larvæ, and when applied directly to the insects by immersing them in the liquid. A number of larvæ in cocoons were immersed for 17 hours in a miscible oil diluted in water at the rate of 1 part in 10. Several hours after removal from the solution one-third of the larvæ appeared to be uninjured and were spinning new cocoons. The balance were almost inactive but none was dead and none died within a week. A similar test was made using 40 per cent nicotine sulphate at a dilution of 1 to 233 combined with the oil solution used above. The larvæ after removal

were all alive but were inactive and none died within 48 hours. About one-third of the insects were alive a month later. Other tests were made for shorter periods of time without satisfactory results.

Fumigation tests with hydrocyanic-acid gas[1] were made on overwintering larvæ in cocoons. The heaviest dosage used with natural atmospheric pressure was 1 ounce of sodium cyanid to 100 cubic feet of space for a period of one hour. With such treatment the larvæ were not killed. Other tests were made in which were used larvæ taken from the orchard in December in enlarged gummy twigs. The larvæ were incased in a hard mass of dried gum and leaves. They were fumigated in a 25-inch vacuum with a dosage of 1 ounce of sodium cyanid to 100 cubic feet of space for one hour, and also with a dosage of double this amount for two hours. Neither treatment killed all of the larvæ.

From the results obtained in the dipping and fumigation tests noted above it would appear to be impossible to free infested nursery stock from this insect by such means.

Parasitism appears to play an important part in controlling the pest, and the attack in the latter part of the season undoubtedly lessens to an appreciable extent the number of moths emerging in the following spring, but sufficient data on the percentage of parasitism occurring have not yet been collected to warrant a definite statement in this regard.

[1] Tests made by Mr. E. R. Sasscer, of the Federal Horticultural Board.

XU

PLATE 5

Laspeyresia molesta:

A.—Peach twig showing summer injury.

B.—Peach twig with mass of gum, leaves, and frass; a type of injury found in fall and winter.

A
B

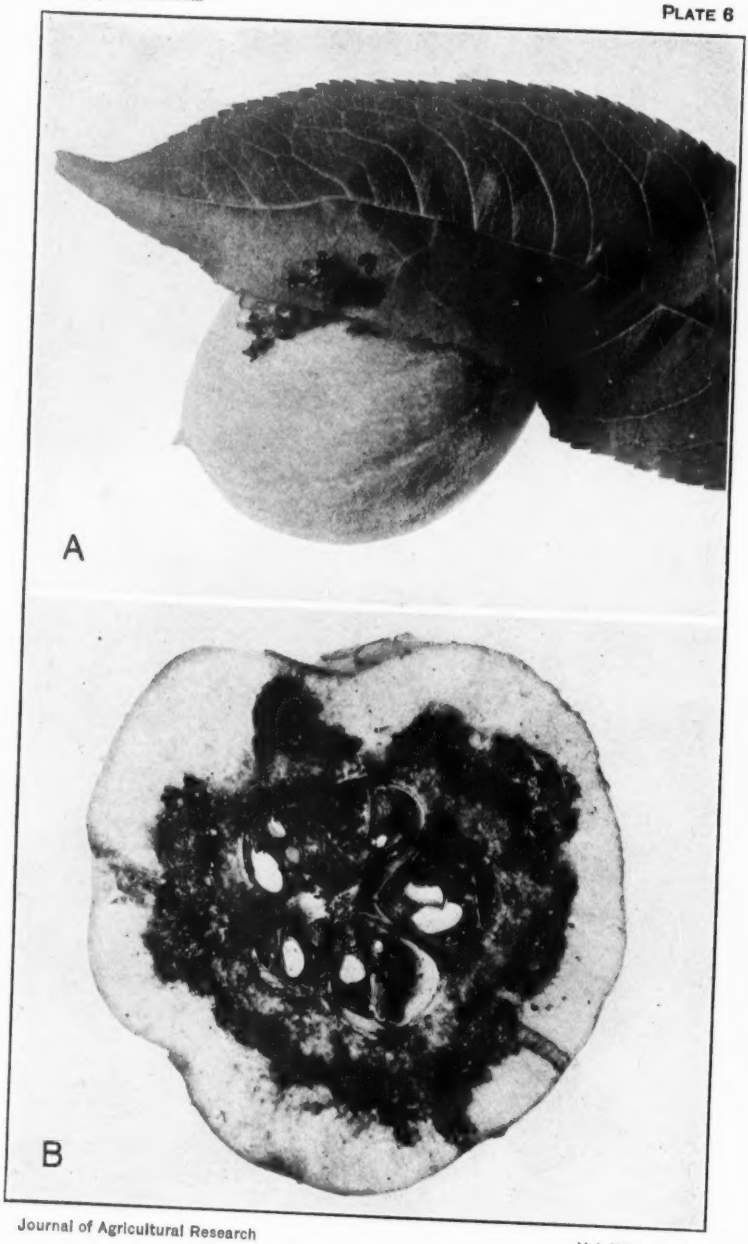

A
B

PLATE 6

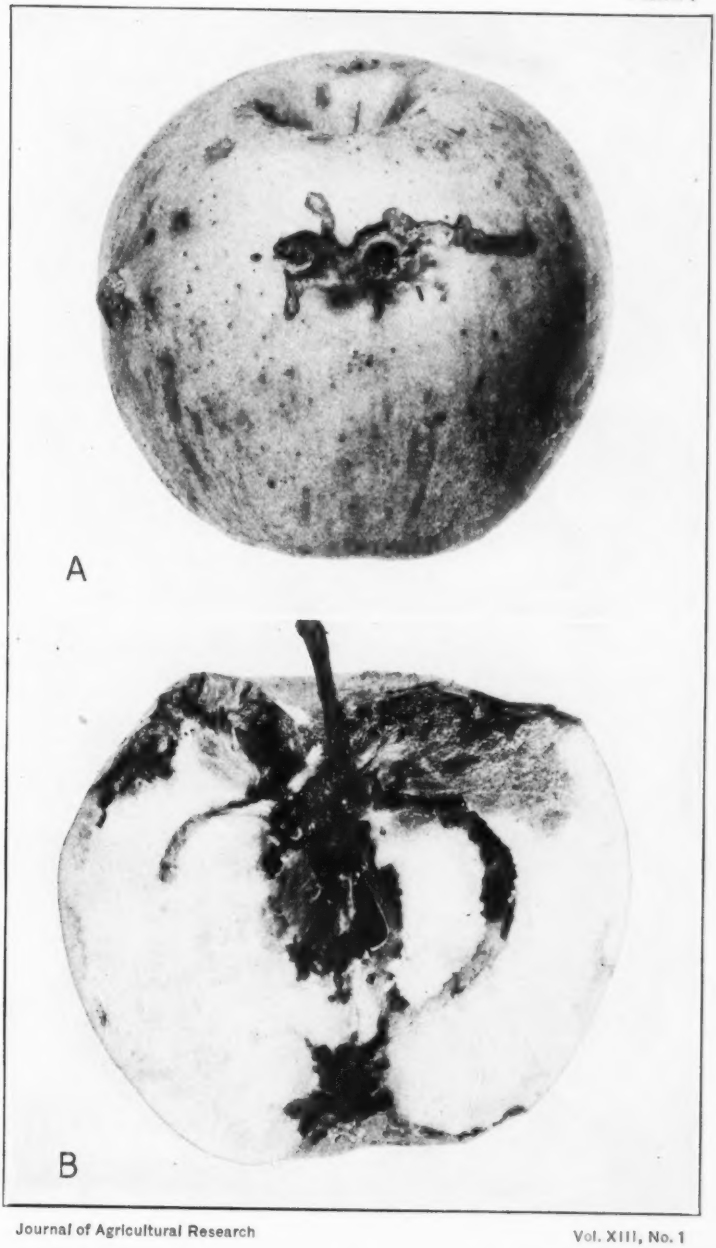
Laspeyresia molesta:

A.—A green peach attacked by the caterpillar, illustrating a common type of injury.
B.—A quince severely injured.

PLATE 7

Laspeyresia molesta:

A.—Typical injury by larva on apple, resembling that caused by *Laspeyresia prunivora.*
B.—Injury to the interior of the fruit.


A
B

Laspeyresia molesta

PLATE 8

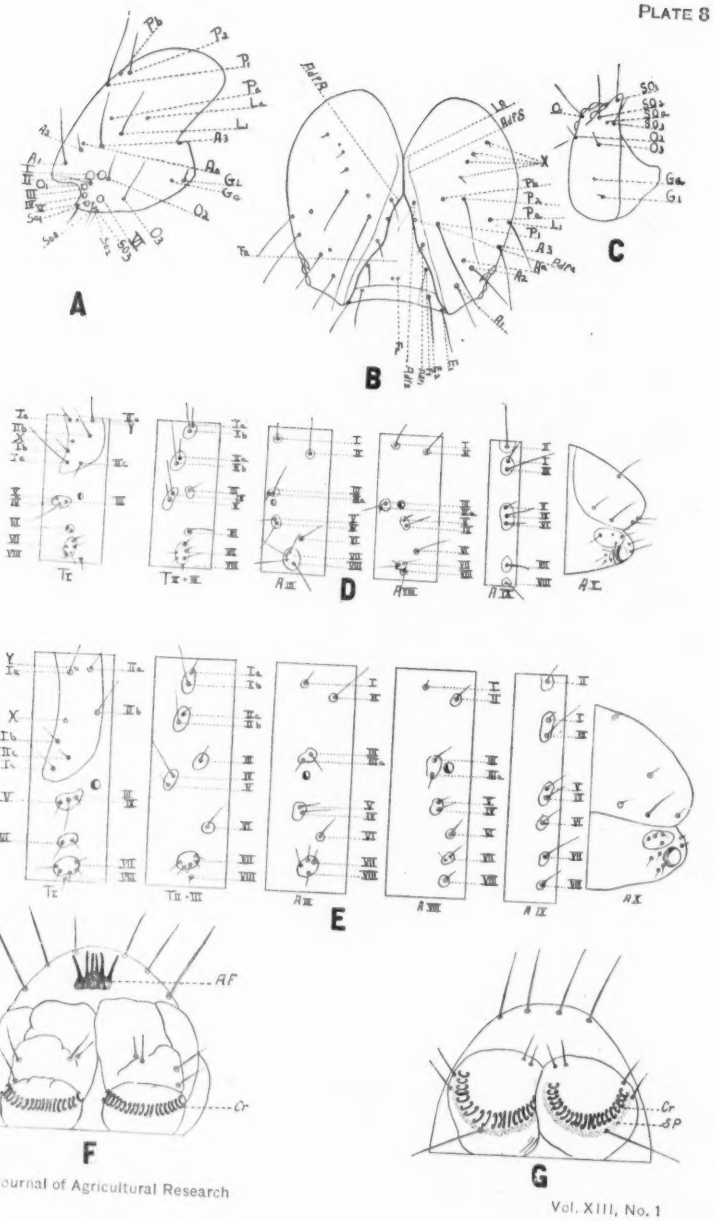


PLATE 8

A.—*Laspeyresia molesta:* Head capsule of larva from side.

B.—*Laspeyresia molesta:* Head capsule of larva from front.

C.—*Laspeyresia molesta:* Head capsule of larva from beneath. A_1, Anterior seta 1; A_2, anterior seta 2; A_3, anterior seta 3; A^a, anterior puncture; Adf_1, adfrontal seta 1; Adf_2, adfrontal seta 2; Adf^a, adfrontal puncture; *AdfR*, adfrontal ridge; *AdfS*, adfrontal suture; E_1, epistomal seta 1; E_2, epistomal seta 2; F_1, frontal seta; F^a, frontal puncture; *Fr*, frons; G_1, genal seta 1; G^a, genal puncture; L_1, lateral seta 1; L^a, lateral puncture; O_1, ocellar seta 1, O_2, ocellar seta 2; O_3, ocellar seta 3; P_1, posterior seta 1; P_2, posterior seta 2; P^a, posterior puncture *a*; P^b, posterior puncture *b*; So_1, subocellar seta 1; So_2, subocellar seta 2; So_3, subocellar seta 3; So^a, subocellar puncture; *X*, ultraposterior setæ and punctures; *I*, ocellus 1; *II*, ocellus 2; *III*, ocellus 3; *IV*, ocellus 4; *V*, ocellus 5; *VI*, ocellus 6.

D.—*Laspeyresia molesta:* Diagram showing arrangement of body setæ on segments. T_I, first thoracic segment; T_{II+III}, second and third thoracic segment; A_{III}, third abdominal segment; A_{VIII}, eighth abdominal segments; A_{IX}, ninth abdominal segment; A_X, tenth abdominal segment.

E.—*Laspeyresia pomonella:* Chart showing arrangement of body setæ on segments. The numbering of segments is the same as in D.

F.—*Laspeyresia molesta:* Ventral view of anal prolegs and caudal end of abdomen. *AF*, anal fork; *Cr*, crochets.

G.—*Laspeyresia pomonella:* Ventral view of anal prolegs and caudal end of abdomen. *Cr*, crochets; *SP*, scobinated pad.

PLATE 9

Laspeyresia molesta:

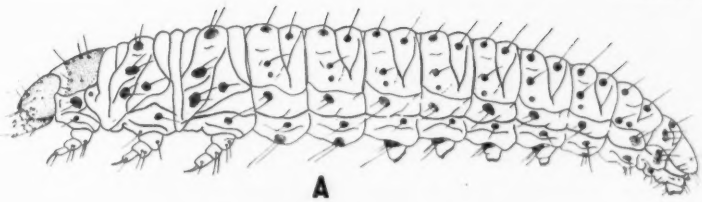
A.—Larva.

B.—Egg.

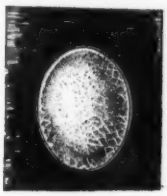
C, D, and E.—Pupa, dorsal, lateral, and ventral views. A_1, A_2, A_3, A_4, A_5, A_6, A_7, A_8, A_9, A_{10}, abdominal segments 1 to 10; *AO*, anal opening; *Cl*, clypeus; *Cx2*, mesothoracic coxa; F_1, prothoracic femur; *GE*, glazed eye; *GO*, genital opening; L_1, prothoracic leg; L_2, mesothoracic leg; L_3, metathoracic leg; *LP*, labial palpus; *Md*, mandible; *MP*, maxillary palpus; *MS*, mesothorax; *MT*, metathorax; *Mx*, maxilla; *P*, prothorax; *V*, vertex; W_1, mesothoracic wing; W_2, metathoracic wing.

Laspeyresia molesta

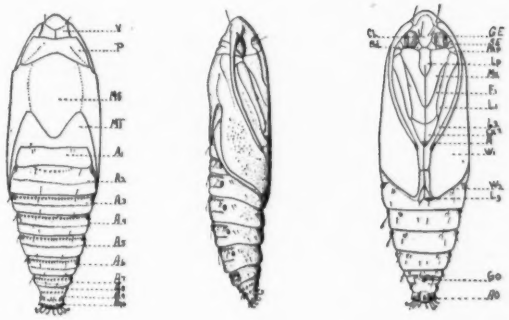
PLATE 9



A



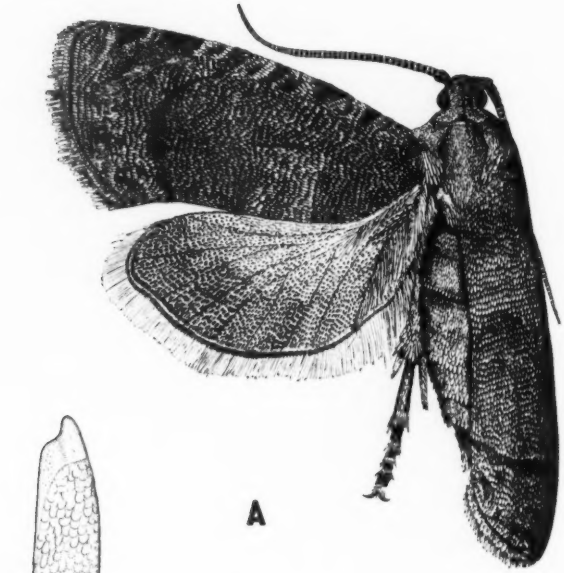
B



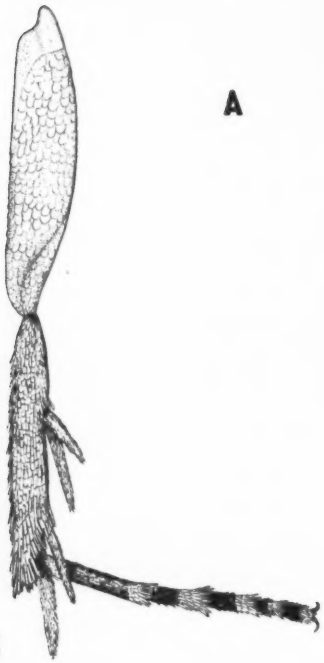
C D E

Laspeyresia molesta

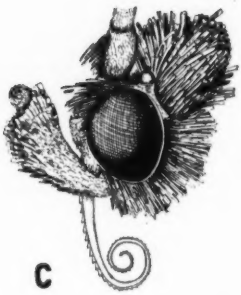
PLATE 10



A



B



C

PLATE 10

Laspeyresia molesta:

A.—Adult.
B.—Metathoracic leg.
C.—Head and mouth parts.

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